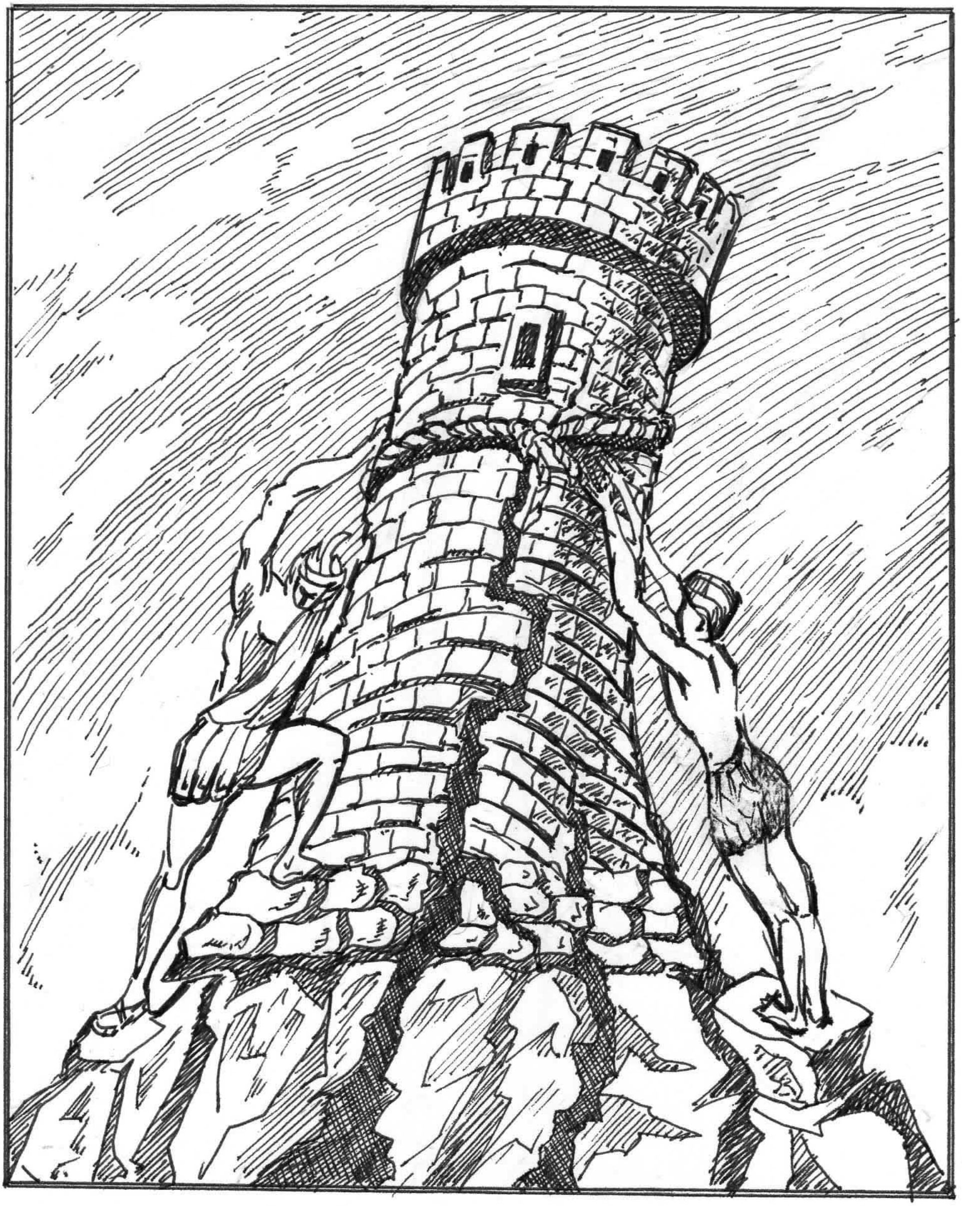

MOMENTS OF
ERTHQUAKE-RESISTANT
CONSTRUCTION HISTORY

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by
B.A. Kirikov

Translated from the Russian
by
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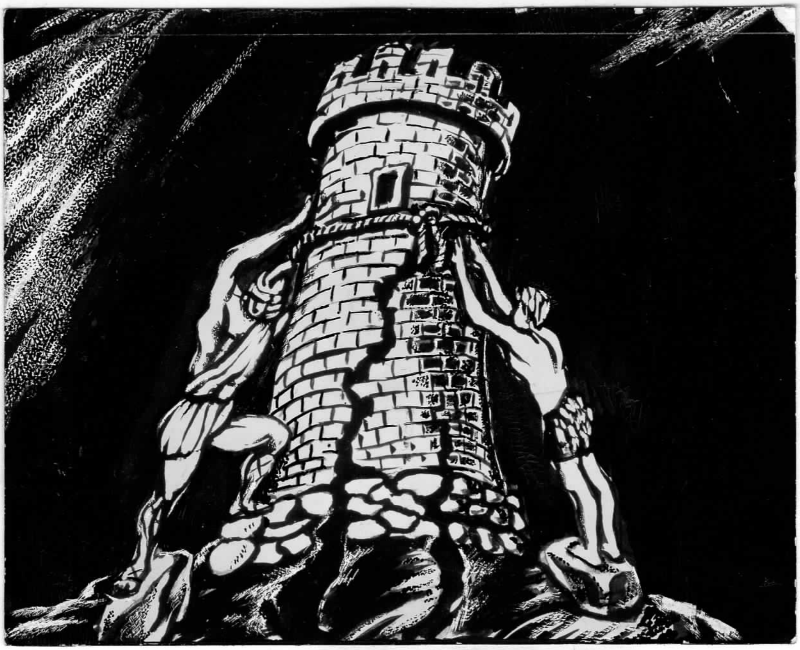

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Preface

I invite you, my respected reader, to take part in this travel over a severe and mysterious world of earthquake-resistant structures. It is severe, because each mistake of a builder in a region of earthquake hazard leads to deaths of people and demolishing of spiritual and material values. It is known that some civilizations have perished in earthquakes. Its mysterious features range from hardly predictable seismic effects, because nobody knows when, where and how they will show themselves, to the most unexpected behaviour of the structure during an earthquake. Well-founded structures built on the grand scale, it would seem for ever, may go to pieces like houses of cards. At the same time, light flexible minarets going into the sky like needles stand without trouble a thousand years, surviving all earthquakes.

I invite you, my courteous reader, to look at the most interesting, to my mind, pages of the earthquake-resistant construction and visit most secluded spots of history. And this is in the literal sense of the word. By this I mean that, in addition to getting deeper hundreds and thousands years into the history, we shall have to get under the foundations of structures, places not seen even by archaeologists, and together with scorpions penetrate into cracks of thick walls, creep under largest domes to reach most inaccessible spots which only house bats and perhaps rebellious souls of sinners. This is all done in order to unveil secrets of ancient builders who created earthquake-proof structures.

Because of the limited space of this book, the author cannot tell you about all earthquake-resistant historical architectural monuments, and, as you know, it can hardly be done by one person. My objective is far restrained. I am going to collect antiseismic ancient and present-day techniques I am interested in, and I hope you are as well, under one cover and generalize them into principles of earthquake-resistant construction. As you will see later, these principles are not so many. Most of them have been revealed far in remote past and are still applied. Design and building materials, construction work techniques undergo evolution and, finally, people change, but the laws of nature remain unchanged resulting in unchanged principles of designing the earthquake-proof structures.

In short, on the basis of fairly limited historical material I selected, I am going to demonstrate spiritual and design wealth of ancient builders we inherited. I wish to give you, man of today, this priceless heritage with a view to help you to control the element of earthquakes.

I wish to express my sincere thanks to remarkable people, Luba Chukhontseva and Oleg Markovich, who have kindly illustrated this book.

What Is An Earthquake-Resistant Building?

Some Words on Earthquake Loads

In our trip for investigating the architectural monuments of the past with a view to studying the techniques of ancient builders, my role is apparently that of a guide. My duties are to select the routes, show everything and state my opinions with which you may agree or not. I'll start with putting you in the way of things. We shall be concerned merely with construction problems, for which reason we shall not discuss the occurrence of earthquakes, propagation of seismic waves, and the more so earthquake predictions. These problems are dealt with by seismology. The only thing I have to tell about herein to make further reasonings clear is the ground motion under a structure during an earthquake.

The ground motion caused by an earthquake is very complex. Its true mathematical description can be performed only by the theory of random functions. In reality, during an earthquake, the ground motion under a building is caused simultaneously by a series of seismic waves each having its own length, period of oscillation, amplitude and velocity of propagation. As a result, all points of the ground under a structure foundation move differently, though in many cases only in a slightly different manner. This depends on the top-view dimensions of the building and the length of seismic waves. Moreover, the building affected by an earthquake starts generating waves by itself. These are primarily waves reflected from its bottom. Besides, like a land vessel, the building starts its roll and pitch motions in the elastic ground medium, thus agitating the ground bulk, with waves propagating outwards in all directions. Try to imagine, therefore, what a complex picture of ground motion there is under the structure during an earthquake. It should be kept in mind that the picture of the previous earthquake will not be repeated during the next one. It may be quite another. What will it be? It can be predicted only roughly. Under such conditions of the so-called incomplete information about earthquakes, construction jobs were carried out by ancient builders and are practiced by present-day constructors. That is why both in the past and at present, one should not fail to study the experience gained in the earthquake-proof construction of past years in order to comprehend it and avoid errors made previously.

Today we well know the essential effect of grounds on the building behaviour during an earthquake. The so-called process of interaction between the ground and the building takes place during which earthquake loads may be aggravated or moderated. Strange as it may seem, the impression is that ancient builders knew it and paid much attention to the preparation of the ground base for structures to be erected. We shall discuss it in detail later.

In addition, in order to avoid unnecessary perplexity, it must be specified at once that the obsolete concept of earthquake magnitude will not be used. The matter is that the earthquake magnitude concept has been introduced to characterize the earthquake intensity, and the earthquake magnitude was determined by the behaviour of non-seismic structures. The question is how can an earthquake magnitude be determined now in seismic regions where all buildings must be earthquake proof? In current practice, however, there is a developed network of seismometric stations for monitoring earthquakes by seismographs. From the current viewpoint, an earthquake must be characterized by actual parameters such as wave amplitude, period of oscillation, velocity of wave propagation, etc. indicated by its records. Generally, use should be made of everything that is needed for present-day computations and clear physical characteristics of earthquake.

Earthquake effects will be best represented mathematically by random fields, when the ground motion under a structure at each point is described by a random function. Let us try to resort further

Fig. 1. Dragon-like model of earthquake

only to clear reasonings and physically vivid images without being absorbed in theory. By way of example, we may fancy the picture of ground motion under a structure during an earthquake. In my opinion, it can be best illustrated by an image of a gigantic snake-like dragon moving under the building by throwing its body into vertical loops in a manner shown in Fig. 1. It well demonstrates the propagation velocity of travelling wave, its amplitude, prevailing periods, and other parameters. To make the picture complete, imagine many such dragons wriggling under the building. These tangles of gigantic dragons desperately convulsing under a structure may give you an idea of the complex picture of ground motion under a structure during an earthquake.

We shall not return to the problems of seismology any more, though it will be meant further that the ground motion under the building is very irregular and depends on the properties of the ground and building itself, and on the type and depth of the building's foundation.

The proposed "multidragon" model of earthquake allows one to see easily the chaos under a structure during an earthquake, which is at the same time governed by certain regularity. Individual spots of the foundation move randomly, as it might seem. During a fairly severe earthquake, the building foundation is drastically torn apart, compressed, twisted, bended, or undergoes all these actions simultaneously. The case is that such a complicated, unpredictable, motion of the structure foundation must be controlled so that the building survives and is saved. At once a question arises: is it feasible to make buildings resist earthquake loads with only approximate information available about the phenomenon? The answer is yes, and this is confirmed by the history of the earthquake-resistant construction. How can it be done? We shall talk about it on the pages that follow. Strictly speaking, the book is dedicated to this problem. It should be kept in mind that current earthquake-resistant construction originates from its centuries-old history.

If you are an observant person, you had many opportunities to note that the ancients were able to accumulate and generalize their previous experience in various fields of knowledge, be it medicine or astronomy. That was the case with earthquake-resistant construction. The history of creating antiseismic structures by the ancients is extremely interesting and instructive.

In short, the construction of earthquake-proof buildings is a task with many unknown variables, ranging from features of the earthquake loads to characteristics of the building involved, and one known variable stating that human lives in the buildings in question must be safe in earthquakes.

Basic Principles of Earthquake-Resistant Construction

Prior to the direct studying of objects that comprise the history of earthquake-resistant construction and satisfying our curiosity, let us inquire into something. We shall try to reveal the essence of the concept—an "earthquake-resistant building". What is it? If treated in a narrow way, then an earthquake-resistant building is such a building which provides safety of people and prevents property damage during an earthquake. Unfortunately, as you may know, this requirement is frequently far from fully met, either due to design errors, poor workmanship, or because of incomplete knowledge of the phenomenon, which did not allow the immediate dangerous earthquake effect to be taken into account. Therefore, those people are right who do not rely on the earthquake resistance of buildings and leave them when the first signs of earthquake are manifest. Though, we hope all will be the other way round in the future: the quality of construction work will be perfect, there will be no errors in the building design, the materials will be durable, light and elastic, and the buildings will become really resistant to earthquake loads and shocks, and on the first earthquake symptoms people will take refuge indoors rather than pop out outside. The bright future of the earthquake-proof construction, as we optimistically hope, will set in, and the term "collapsed building" would be encountered merely in ancient manuscripts.

The above-mentioned is the definition of an earthquake-resistant building made from the so-called humanistic viewpoint. The definition can also be made from the economic standpoint. For example, the cost of restoration work after an earthquake should not exceed some percentage of the building cost. From this point of view, it is more profitable for some towns to take no antiearthquake costly measures, provided people are prevented from being killed or injured, say, by earthquake prediction and early evacuation. In this case it is better to construct a town anew after each severe earthquake once in a hundred or two hundred years because earthquakes occur not so often, while anti-earthquake measures are very costly.

I do not know how a more general definition of an earthquake-proof building can be formulated, but in my opinion, it can and must be done. Maybe, the theory of probability will help us. For example, in short: "Earthquake-resistant is a building whose probability of damage by an earthquake of expected intensity must not exceed a certain magnitude within the entire building's service". In any event the intuitive notion of an earthquake-resistant building may simultaneously imply specific features of the structure, people safety, tolerable level of damage, and economic indexes.

According to the objective of this book, we shall dwell upon one aspect of such a notion as an "earthquake-proof building", namely, its structural features, considering them in historical evolution. I want to create an interconnected and integrated picture of the earthquake-resistant structure world instead of naming antiseismic measures in chronological sequence. My proposal is as follows. In order to logically connect all chapters of this book, each being dedicated to a historical/geographical region of the world, I will formulate the fundamental principles of designing the earthquake-proof buildings. On the basis of these principles antiseismic structural designs will be considered, which were used in ancient structures in various countries of the world in different ages.

In compliance with mysterious characteristics of earthquake-resistant structures, the number of these principles naturally equals the magic number seven. These are:

1. The principle of symmetry. The weights and stiffness in a structure must be uniformly and symmetrically distributed with regard to the planes of symmetry passing through the structure's centre of gravity.
2. The principle of geometrical harmony. Definite proportions between the height, width and length of a building impart to it the resistance to earthquake loads. Any of its dimensions should not be too great in absolute magnitude compared with the other dimensions.
3. The principle of weight minimization. The structure must be as light as possible and have its centre of gravity as low as possible.
4. The principle of ideal material. In the structure use should be made of tough, light, elastic materials; structures made of these materials should have uniform properties.
5. The principle of closed contour. The load-carrying elements of a structure must be coupled to each other to form closed contours both in vertical and horizontal planes.
6. The principle of fundamentality. The foundations of earthquake-proof structures must be firm and lay deep. It is desirable that the foundations are based on pliable beds or special substructures replacing weak soils to provide a uniform and firm ground base.
7. The principle of seismic insulation. Use should be made of devices that reduce the intensity of oscillation processes conveyed from the ground to the building.

Certainly, the requirement for high quality of construction work is not included in the number of earthquake-resistant construction principles. This goes without saying in any type of construction.

The above-listed principles can be integrated into a general law of earthquake-resistant construction: to erect earthquake-resistant structures all possible and impossible should be done in order to prevent concentration of stresses caused by earthquake loads in any part of the building. This does not allow overloading of building elements. Any overloaded building element is much more prone to a ruin. Destruction of one element leads to overloading and destruction of others resulting in avalanche collapse of the whole structure.

The seven principles offered are presented as generalization of the centuries-old experience in earthquake-resistant construction. Certainly, something else can be added to these principles, which I shall be doing along our trip. As we shall see further, all the above-mentioned principles will be found in some ancient structures. Moreover, you must be ready to encounter all sorts of unexpected facts, since the structural implementation of these principles may take most fantastic and daring forms.

I want to tell you that the above-listed principles deserve the same attitude as any other principles, i.e. it is not necessary to completely observe them. Certainly, very tall or asymmetric structures may be erected, but in this event some additional measures should be taken to make them withstand earthquakes.

Maybe, the thought flashed through your mind how such special antiearthquake measures taken in ancient structures can be found, described and analysed properly. I agree with you. It is quite a problem to distinguish just antiearthquake measures from all structural techniques of a given structure.

Of course, there are no drawings of ancient structures preserved, the more so comments to them, and it is most likely that they did not exist at all, since the structures were laid out directly on the terrain. Frequently, there have been left no such structures, in particular most ancient structures, which were used later as stone quarries. Only scanty information or ruins have been left of many. There are, however, such that stand up to our days showing their construction perfection. Therefore, we can't know the thoughts of ancient architects creating their masterpieces, what design decisions have been made by them to protect their buildings against earthquakes, and how they generalized the experience gained from their predecessors. It may be that they did not treat seismic loads separately but considered the whole set of external loads all at once.

What to do? I believe the only way is to consider ancient structures from the present-day standpoint on seismic stability of buildings and to analyse them accordingly. Certainly, errors are inevitable in our investigations. In some cases, we shall attribute something to ancient builders they did not think of. In others, on the contrary, we may not notice some structural hints utilized by ancients to improve the earthquake resistance of structures. To my mind, however, there is no other way to study the centuries-old experience of earthquake-proof construction from the current standpoint. Looking for signs of antiearthquake measures in ancient structures, we should keep in mind that the element of earthquake that shot up to the surface gathered in the rich harvest of human lives and sufferings not once (Fig. 2). That is why, we must study the manifestations of earthquake to know how to fight it.

The objective of this book is to show how the experience of ancients can be utilized for construction purposes of today.

How Are Buildings Made Earthquake-Resistant?

Prior to answering this question intelligibly, I will consider the following two problems as a preliminary. The first is straightforward and somewhat primitive. How do earthquakes ruin buildings? The reply is as primitive. With the treachery inherent in it, an earthquake seeks a weak spot in the structure involved and hits just this spot to start destroying the whole structure. The destruction of this type may have its origin in a weak foundation and on a weak soil bed, and in addition the foundation may have been affected before the earthquake by non-uniform settlements. It is this foundation that the destruction will start with. With a tall structure stretching into the sky, a weak place may be the top part, rather than the foundation, which when widely swung during an earthquake is torn away by inertia forces it develops as a result of high accelerations. In a frame building column-to-beam joints

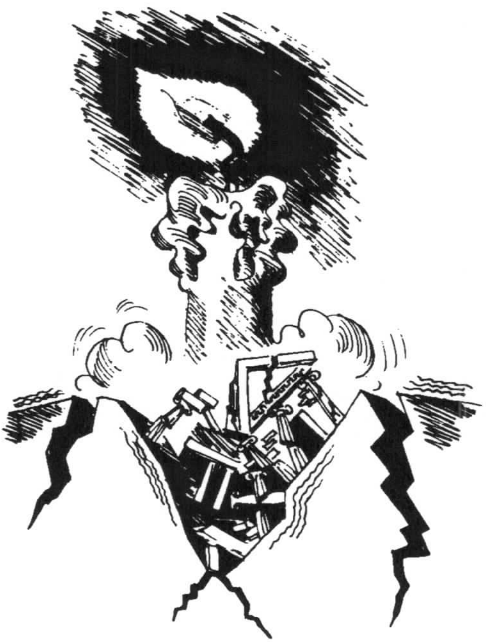

Fig. 2. Suggested poster for regions of probable earthquakes

in the ground floor may form plastic hinges due to gigantic shearing loads. The building will undergo geometrical distortions and collapse owing to this. In an arch the top locking portion may fail, if it is not strong enough, or, on the contrary, insufficiently yielding. Finally, phenomenon close to resonance may occur when structure natural frequency coincides with prevailing frequency of the earthquake action. In this case, heavy deformation caused by stresses in the load-carrying elements may overcome ultimate strength of the material with resultant failure in the weak spot. All structure tests with the aid of some devices simulating earthquake effects are made to detect these weak points and improve them.

Now, there is another, somewhat philosophical question. Did the standpoint of ancient builders related to an earthquake-proof building differ from the notion of today? To my mind, it differed essentially. Note that I unintentionally idealize ancient builders.

They are really very likeable as looked at from our time of low-quality construction. There are reasons to say so. A more ancient structure almost always shows good quality and thorough fitting of stone blocks to each other. An example may be taken from other than construction field. The black-lacquer vessels of the Greeks, the fifth century B.C., are far better than similar vessels of the third century B.C.

I believe the difference between the earthquake-proof building notions of ancient and contemporary builders is as follows. A contemporary builder may ask: "How can this non-seismic building be made earthquake-resistant? What can in this building be reinforced?" Very likely, the ancient builder couldn't ask such a question. In his view, as may be judged by ancient architectural monuments, an earthquake-resistant building differs in principle from the conventional building. In the former the idea of providing the resistance to earthquake loads ought to penetrate everything from the proper treatment of the ground under the foundation to the tip of the dome. Each stone of masonry seems to be thought about to place it better as dictated by shape and structure and secure it so that it cannot be knocked out by earthquake shocks. In addition to tying stones together, the mortar in each joint ought to protect the masonry from water penetration. Otherwise the water would cause gradual deterioration of the masonry. Hydraulic insulation of the masonry also adds to antiearthquake stability of the building. The paving made around a building to prevent water from getting under it and into the subsoil under the foundation is also a seismic stability feature. Sometimes, these, seemingly minor structural elements, play a major role in making a building resist earthquake loads. Further, we shall talk about construction antiseismic measures, and I will do my best to lay emphasis on what is of interest in ancient structures whose builders could solve several problems in a comprehensive way using one method. For example, a sand pad under the foundation of a wall may absorb earthquake shocks and drain water away from under this very wall of air-dried bricks. There will be many of such examples.

After all "lyrical" digressions, we can answer the main question of this section. How are earthquake-resistant buildings constructed? Conventionally, three basically different approaches can be employed in designing the earthquake-proof buildings.

The first most popular approach consists in creating a structure of increased strength capable to withstand earthquake expected in a given region without great damage. According to this approach, the building must be reinforced with a respective rise in its cost, so that it is sufficiently reliable, but not too expensive. An ideal implementation of the given approach to erecting the earthquake-resistant structures would be a tilting-doll building, such a robust fellow, that could float steadily in seismic waves without substantial damage, though being widely swung.

The second approach is as follows. It is known that the stronger and firmer is the tie between the building and the shaking ground, the higher are seismic loads arising in the building, because shaking is better transmitted from the ground to the building. And what will be the result of reducing these loads by weakening the tie between the ground and the building? To this end, use is made of various earthquake protection elements, such as sand interlayer, clay cushions, rush belts, sliding belts made from metallic plates, rubber padding, balls, ellipsoids, air cushions, and springs. This approach existed in remote past and is actively developed in many countries today helping to create cost-effective and reliable earthquake-resistant structures. We shall talk about structural techniques of this approach in detail on the pages devoted to modern times. Perhaps, it will be correct to call this trend a system of passive earthquake protection, in contrast to the third approach in which the systems of active earthquake protection are utilized.

According to the third approach, the buildings are furnished with some devices that change dynamic properties of the building when it gets in resonance to help it out of this state. Actually, this is the latest method of erecting the earthquake-resistant buildings, since in this event the building is equipped with power units controlled by robots that process current information about the earthquake taking place to make the building respond to earthquake loads and vary its properties to get out of resonance. In fact, these are building-robots.

On the other hand, this is the most ancient method of protecting buildings from earthquakes. The matter is that any building can alter rigidity, as if changing its structure and the period of natural oscillations. However, in conventional buildings the period of natural oscillations may vary approximating the period of ground earthquake-caused shaking with resultant resonance and possible collapse, or moving away from the period of shaking with abrupt drop of earthquake loads. In the present-day buildings equipped with robots operations of the active protection system are aimed at getting the building out of resonance.

There is an example showing how a building without any robotization is capable of changing its structure and adapting itself to earthquake effects. Recall the 1948 Ashkhabad earthquake [1]. A mosque built of burnt brick, 1911, Svoboda street, on strong lime mortar, in the best traditions of the Central Asia architecture comprised a central nonagon drum (Fig. 3), 33 m in height from the base to the dome top, and two more far lower drums with arch ceilings located in a concentric manner. The latter drums were ancillary buildings of the central structure. When assembled, the structure was very stiff, i.e. the period of natural oscillations was small. Evidently, the ground prevailing period of shaking caused by a near earthquake was also small in this site for which reason the mosque underwent resonant shaking during the earthquake and was in danger of collapse. However, the mosque started fighting for life. The central drum and ancillary buildings were united into a single whole, making the mosque very stiff. The struggle started with failure of the links between the central drum and one of the ancillary buildings, which is illustrated by the figure. Further, each part of the structure was fighting for life separately, depending upon its structural features. The pillars of the ancillary building were sheared, thank Allah, they were not too strong. The shaking energy transmitted from the ground to the ancillary building dropped at once, since they were now coupled merely by friction. Here you have a prototype of sliding belts we shall talk about later. The idea of such antiearthquake protection is suggested by the nature. The central drum, whose pillars were too strong to be sheared, behaved in a different way. It decided to sacrifice the integrity of walls above the ground and first tiers of window apertures. Their failure resulted in cracks at 45 degrees to the horizon. Thus, vertical pillars were formed of the continuous drum of the dome. The pillars were free to slide relative to each other

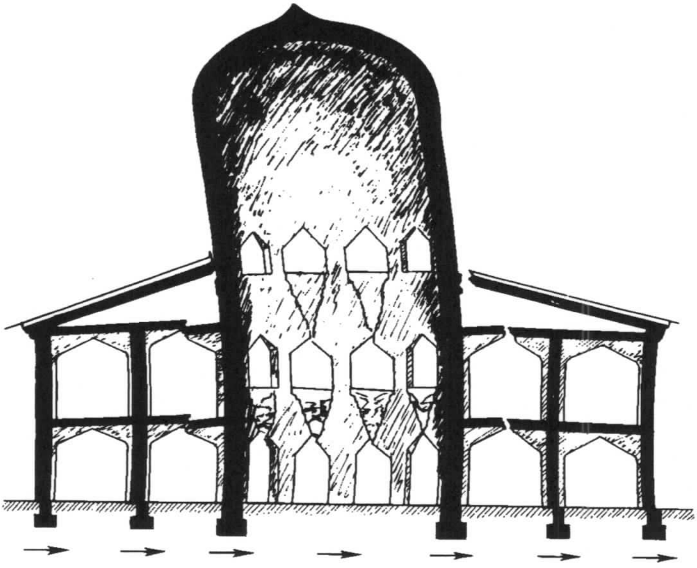

Fig. 3. Selfconversion of mosque building from rigid to ductile

as they were tied merely by friction. The stiffness of the central mosque drum abruptly decreased due to elimination of the ties the function of which was performed by the arches above the windows. The central part survived too, since the dome was supported by a flexible, rather than stiff, structure with a large nonresonance period of natural oscillations. This restructuring of the mosque design scheme had saved its life, and the mosque proudly and victoriously carried its minarets above the ruined city. It would be good to restore the mosque, but it was demolished in 1960's, which was easier for the ignorant persons involved. The arrow-shaped mosque dome collapsed only after falling to the ground.

In order to finally elucidate the difference between the systems of passive and active antiearthquake protection, let us consider the so-called ideal examples of both systems. If a building were suspended from a balloon and lifted above the ground, it would be a system of passive antiearthquake protection, and the building

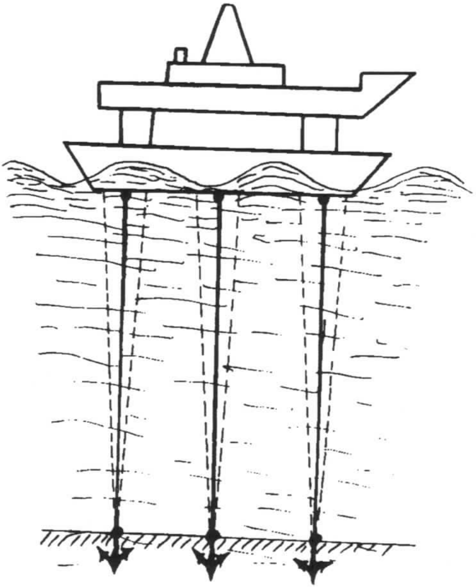

Fig. 4. Offshore floating oil-extracting platform

would be fully isolated from the ground shaking during an earthquake at all times.

If a helicopter building were constructed that would stand on the ground and would take up only at the command from the relevant devices warning the helicopter of an approaching earthquake wave in order to let it pass, this would be the active antiearthquake protection.

If you assume that the examples of ideal earthquake-resistant structures I named are pure abstraction, you make a mistake. As to a building suspended from a balloon, there is still no such building because the construction materials are yet too heavy. However, a structure floating in water and supported by water already exists in the form of offshore oil-extracting platforms (Fig. 4). These gigantic structures, which present great danger to the environment, may be used in regions of highest earthquake risks. These have the same principles of earthquake protection as a building suspended from a balloon.

Now some words about a helicopter building, which is also unreal yet. A building can be easier unstuck with the aid of a magnetic field, water jets, air cushion. We shall discuss structural implementation of contemporary antiearthquake protection systems at the end of our historic trip.

The three above-mentioned approaches to construction of the earthquake-proof structures make it clear that the seven principles of seismic stability apply solely to the first approach according to which buildings are made highly strong with stiffnesses ensuring their nonresonance state during an earthquake. As a matter of fact, it is not quite like that. If a building of the second type supported by seismic insulators does not satisfy the structural symmetry requirements, an earthquake would cause such torques that some seismic stability elements, let it be cast-iron balls, will be overloaded and may be damaged; this will destroy the whole antiearthquake protection system. Even in a helicopter building the structural symmetry principle must be met, not to mention the requirements for lightening the structure. In short, the above-mentioned principles of earthquake-proof construction are universal and apply to all three types of earthquake-resistant structures.

So, the inaugural lecture is delivered. I hope it has introduced the reader into the world of earthquake-proof structures. We have outlined the group of problems to be considered in our history of seismic stability. The problem is posed and has to be tackled.

Three Great River Civilizations

At the Dawn of the Mankind History

What is the suitable time of the mankind history at which our trip through the history of earthquake-resistant construction should be commenced? In order to make no mistake and be scientifically impartial, it is best of all to start with the creation of the world. As soon as Adam and Eve settled in the garden of Eden, which were, as you know, situated in now and then windy and rainy Mesopotamia, they immediately had to show concern for dwelling. So, the first people on Earth were faced with the problem of constructing an earthquake-proof house, since the plains of Mesopotamia on which the rivers Tigris and Euphrates flow feature high seismic activity. Note, that known for similar increased seismic activity were the valleys of the rivers Indus and Nile. The famous great civilizations we shall talk about later in this chapter were located in these valleys. It may be a simple coincidence, but the fact is that ancient civilizations arose in the areas of high seismic activity.

Already Adam had to show concern for an earthquake-proof house. Most probably, proceeding from the local conditions of the garden of Eden and archeological excavations dated back to the 4th millennium B.C., Adam built a hut of interweaved twigs smeared with clay. Here you have the first earthquake-resistant structure that comprises a strong and flexible skeleton and clay fill. We shall encounter the idea of creating skeleton structures later, in the course of the entire history of mankind. Dwelling houses that comprise a wooden skeleton and a filler were and are built now. As a thousand years' history shows, such houses feature good resistance to earthquakes, because all principles of earthquake-resistant construction are met. We shall later speak about the details of this seismically stable structure originating from Adam.

Now some words about the most ancient monumental structures left after unknown civilization whose purpose and construction are difficult to define and date. These are megalithic single-type structures which can be found from Japan to France and England. Their existence sets one thinking of ancient civilizations perished, persons from other planets, and the like. However, this is not the point now, but the fact that many of constructions situated in seismic regions have stood to many earthquakes in the course of their life covering several thousands of years and still remain well preserved. I can hardly imagine that these structures built of supergigantic stone slabs were created by people wearing animals' skins. It is clear that they were erected by an organized society with its own engineers and even academicians, as we understand it now. Those specialists were people who designed the structure itself and developed the techniques of construction work. We shall never know whether they thought of the earthquake resistance of those structures or not. To my mind, they did not, but they had their own, close to ours, concept of providing the general stability of a structure affected by any element. In order to convince you of this, let us consider a couple of examples. An example (Fig. 5) is a two-level dolmen erected in a very harmonious manner near the settlement of Gorikdi, Azerbaijan [2]. It is made of ten stone plates (slabs) thoroughly fitted to one another and about equal in thickness; the dolmen is almost square in plan. Practically, all principles of the earthquake-resistant construction are implemented in this dolmen. Stiffnesses and weights are uniformly and symmetrically distributed in it. The bearing joints have ductile hinges. When a certain degree of displacement is exceeded, the slabs involved butt against each other to form ties which become engaged to limit the amplitude of system shaking. At the beginning the structure works in a ductile manner and then, when displacement grows, as a stiff nonlinear structure. Many other scientific terms can be mentioned that were unknown to the builders of this most

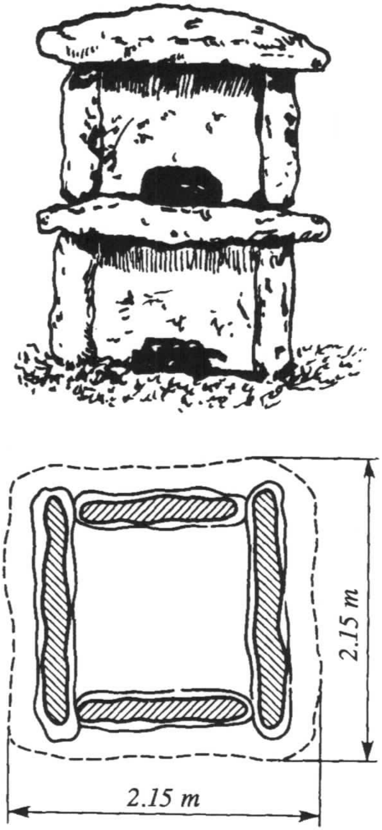

Fig. 5. Two-tier earthquake-resistant dolmen

ancient dolmen. From the contemporary viewpoint, a bit excessive weight may be, perhaps, held against this structure, but even this is a moot point. As we shall see later, the Egyptians had used the weight principle in place of cement.

There are many various megalithic structures in the Caucasus. An example may be given even of a typical dolmen that dates back to the Bronze Age. These dolmens were built single-storied, trapezoidal (for stability) in plan with a wide front and narrow rear walls. There were special grooves to secure these walls. Such a

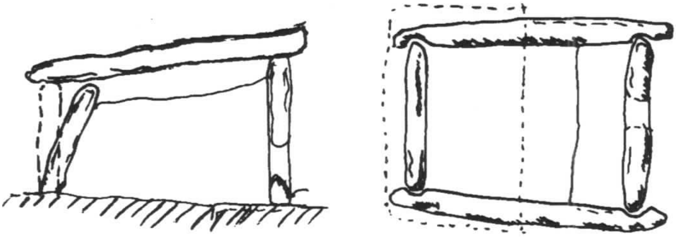

Fig. 6. Earthquake-proof dolmen in Georgia

dolmen located near the settlement of Esheri, Georgia [3], is shown in Fig. 6. The top slab is from 4.8 to 5.2 m wide, 3.7 m long, and 0.5 m thick. Its weight is 22.5 tons. As you see, it is a fairly firm structure. It was this structure that stood several thousands of years even under seismic conditions. Now we shall consider examples of non-standard ancient structures.

The work [4] contains figures of clay models of workship wheeled structures, even three-storied, found in excavations. Ancient Indian wheeled temples have also been mentioned (Fig. 7) [5]. It is known that use was made of wheeled houses to accompany ancient sovereigns during their campaigns. What is it? Maybe, ancient rulers wanted to travel in comfort without any risk, including the hazard of earthquakes for which reason an earthquake wheel-shaped insulating device had been invented. Certainly, it is not so, although a wheeled temple is for sure an earthquake-proof building. We shall encounter this situation frequently. However, hereinafter we shall throw aside our doubts and consider everything improving the earthquake resistance of an ancient structure to be an element of antiearthquake protection from our modern standpoint, regardless of what the ancient architects thought, because we'll never know it.

We shall not any more dwell upon prehistoric builders and move on to the most ancient civilizations. It follows from the above-said that structures were erected in the remote past quite intelligently. Thus, the foundations for substantial approaches to erecting the monumental structures, which we shall further discuss, seem to have been laid.

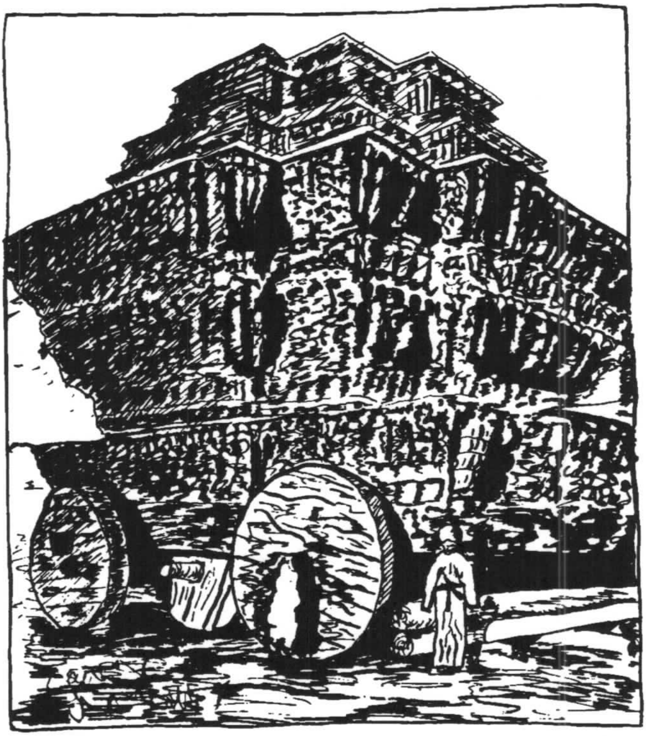

Fig. 7. Indian temple seismically insulated by wheels

Harappeans in the Valley of Indus

Our acquaintance with the construction skill of the three great river civilizations such as the Harappeans on the Indus, Sumerians in the Tigris and Euphrates valley, and Egyptians along the river Nile will be started with the first one. These three civilizations had much in common. They grew on fertile lands of river valleys. The necessity to control the river floods and irrigate lands has united individual tribes into centralized states with towns and villages with resultant development of urban construction, digging channels and making dams, erecting houses, palaces and temples. These three civilizations existed already in the 4th millennium B.C., with close active trade and political interrelations. Their field of activity also included the Minoan-Cretan Culture [6].

The Harappa Civilization far surpassed in size the two others taken together. This civilization was discovered not long ago, in 1920, and is, thus, studied less than others. We do not know when the Harappa culture began to develop. But as early as the 33rd century B.C. this urban civilization is known to be prospering and surpassed the other two civilizations in urban development and culture level. Its prosperity ended in the 15th century B.C. Many similar-type towns, settlements and villages were discovered over the vast territory of the Harappa Civilization. There were also two capital cities: Mohenjo-Daro and Harappa. No other such cities were discovered. The regular rectangular layout of these cities is striking. Broad streets oriented in compliance with the cardinal points were built over with multi-storied buildings made of baked and air-dried bricks. Model projects were obviously used to build standard-brick houses. There were city networks of water supply and sewage. The level of construction culture of that time is witnessed by the following fact. Already then almost each dwelling had a shower and a toilet, while more than four thousand years later there was none in the palace of Versailles.

The Harappa Civilization is most vividly represented by the best preserved largest city of Mohenjo-Daro, which means a "grave mound" in the Sindhi language. It is this mound with which the talk about the earthquake resistance of buildings in that civilization is started. Two zones can be seen in the ruins of Mohenjo-Daro, an elevated and a lower zones. The elevated part carries most important structures: a large bath, a large granary, an assembly hall, and others. Situated in the lower part are dwellings. So, the elevated part is a man-made platform built of sun-dried bricks. Though, this is other than the light and durable sun-dried brick that was used in Mesopotamia. Cut straw was added to the latter brick to make it suitable for earthquake-resistant construction. Depending upon the relief of the terrain, the thickness of the artificial platform varies from 6 to 12 m. The platform top surface underlying the structures is strictly horizontal. Such platforms were erected by the river civilizations to protect structures of importance against floods. At the same time these platforms (stages) served as an effective antiearthquake measure. How these platforms worked will be shown later when we reach the earthquake-proof construction in Mesopotamia. The story will then be more timely since used in Mesopotamia were more perfect and diverse platforms for structures than clay hills as was the case with the Harappa.

The artificial platform for capital structures of Mohenjo-Daro has a good foundation. The Harappa Civilization underwent several disasters with grievous aftereffects. A case is recorded when the city of Mohenjo-Daro was fully flooded by the Indus waters when a mud eruption formed a gigantic dam across the river. There is even a hypothesis that the Flood legend originated just from the valley of Indus, rather than Mesopotamia. Because of great floods and mud avalanches the cities of Mohenjo-Daro and Harappa were several times ruined and left by the citizens. After each disaster, which sometimes took up to 100 years, the citizens returned and reconstructed the city following the old planning. Archeologists discovered seven towns buried one above another in the city of Mohenjo-Daro and six towns in Harappa. All these buried towns were used as a foundation for the man-made stages of the town being restored. The attention of archeologists was drawn to the fact that the deeper a town was in the ground, the more ancient it was with a higher quality of brickwork. A stone dam was also found, which points to the fact that the citizens tried to control mud-laden avalanches overwhelming the town. Nevertheless, Mojenjo-Daro was buried under a layer of silt and sand as a result of most severe earthquake that occurred 140 km to the south and changed the valley of Indus beyond recognition. As was mentioned, this most ancient civilization widely used construction typification and standardization which far later found wide application only in our time. There existed literally standardized projects of dwellings and basins for bathing. Still more so, similar, thick-walled (up to 12 m), citadels on a man-made stage from 9 to 15 m high, 190 by 380 m in plan, with towers rose above large towns. The largest building discovered, resembling a palace, was 170 by 230 m in size. It should be noted that the Harappeans did not erect mighty tombs, temples, king palaces depressing man, which we shall see later in Mesopotamia and Egypt. On the other hand, the dwelling buildings fairly of the same type produce an impression of equality and social justice as if existed at that time.

So, it is clear that citizens of the ancient Harappa Civilization through bitter experience well learned the phenomenon of earthquake that remained mysterious till our days. What did they do to protect their structures against earthquakes? The answer to this question is far from being simple. The written language of these people has not yet been interpreted, excavations made are still few, and what is excavated deteriorates because of ground water salts. But I will still try to outline the general picture of the earthquake resistance of the Harappa building structures.

From builders' viewpoint, the Harappa Civilization may be called a civilization of brick. There everything was built of burnt or air-dried bricks. Something alike we shall see three or four thousands of years later, when we reach Central Asia. It should be noted, however, that the brick burnt by the Harappeans in wood-burning kilns was not so strong as the high-quality strong brick sounding "la" produced in Central Asia. But their bricks were strong enough to be successfully used by the English in the construction of Indian railways at the beginning of our century. The brick is a stiff, but brittle material and in order to use it in the earthquake-resistant construction, special constructive methods should be employed to impart elastic-ductile properties to the whole structure. One of these methods is the use of a ductile mortar which did the Harappa builders. The more so, it was in such abundance everywhere around them that tended to overwhelm the whole city. It was river silt. At that time, they already knew a strong, but stiff lime mortar which was, probably expensive. Besides, the weak silt mortar made it easy to pull down old buildings in order to erect new structures from the same bricks. As a result, the structure built of such stiff material as brick, becomes ductile at the expense of the mortar, particularly if the seams between bricks are thick. It is exactly what an earthquake-proof structure needs. However, it would be wrong to think that a tying mortar in an earthquake-resistant structure must be of low strength. In an ideal case, it should be tough and ductile, but in the structures built by the Harappeans it was only ductile to affect their earthquake resistance. In this case, a measure to determine seismic stability would come in handy, if it existed.

Let us divert our attention from the Harappa to consider the following. Of course, there is no clear boundary between earthquake-resistant and nonresistant structures. Buildings least resistant to earthquakes made without taking into account seismicity can stand to an earthquake of certain intensity without destruction of load-carrying structures. And what is more, two different-type structures designed for an earthquake of similar magnitude may fail at earthquakes of different magnitude; everything depends upon their structural schemes. In order to examine all these paradoxes, we need a measure of earthquake resistance. As I said above, the best results would be ensured by a measure indicating the probability of building destruction by an earthquake of a given magnitude (intensity). Then nothing would be easier than to compare buildings by their resistance to earthquake loads. This building nonresistant to earthquake has such-and-such probability of being ruined by an earthquake of a given magnitude, a present-day framework building—another probability, and this Greek temple—still other probability. With the measure available, comparison can be made. But to determine this probability is quite a problem, though fully solvable. Fortunately, this book is not of the level at which this problem is considered in detail. Therefore, we shall return to our Harappeans.

The use of ductile, elastic mortars in brick-work adds to its earthquake-resistance property, i.e. decreases the probability of building collapse, since the ductile structures reduce the shock energy transmitted from the ground to the building during an earthquake. On the other hand, low-strength mortars, which decrease the strength of a structure, enhance the probability of its collapse as it can now be ruined by an earthquake of a magnitude lower than in the case of strong masonry. From the viewpoint of earthquake resistance, each structural improvement can be assessed like that. As you know, a part of the Mohenjo-Daro city was raised on an artificial platform made of air-dried bricks. Thus, all buildings on that platform (stage) had a uniform base to provide equal transmission of earthquake energy from the ground to the building provoking no stress concentrations. Besides, the platform is built of loose material which also absorbs the earthquake energy.

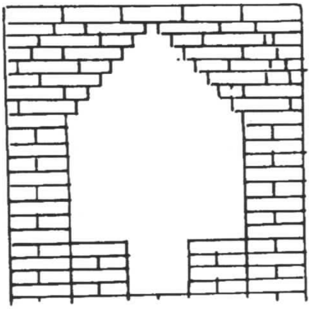

Fig. 8. Sewage tunnel of Harappeans

As you know, the erection of buildings on such stages adds to their resistance to earthquakes. In addition, the foundations of the Harappa structures were made of plastic clay. With structures of importance this cushion of plastic clay was laid under the whole building. Such clay and sand cushions under buildings, which we shall encounter many times, are very effective antiseismic measures. The function of soft ground cushions is clear: they reflect earthquake waves and absorb earthquake shocks conveyed to the building. This is actual seismic insulation.

Now some words about the construction of walls. The ground storey was usually built of burnt bricks on a ductile silt mortar. A point of importance was the order of brick laying, the wall strength and homogeneity being dependent on that. Figure 8 shows the design of a waste-water disposal tunnel whose ceiling is laid like a corbel arch with successive courses of masonry projecting farther inward as they rise on each side of the gap. The figure shows that bricks are laid in a stretcher manner, i.e. flatwise, and in a header manner, so that the brick edge is seen, with bonding the underlying seams between bricks. This brick laying imparts to the wall uniform properties to ensure the earthquake resistance of a structure. The burnt brick of Harappeans was somewhat greater than the present-day brick, the side ratio being 4:2:1. This multiple proportion of bricks allowed one to erect homogeneous, solid brick blocks using any type of masonry to provide seam bonding. By the way, the Harappeans used only corbel arches, while the voussoir brick vaults were unknown to them. The next storey above the ground one had a wooden framework coated with clay or was walled up by air-dried bricks, i.e. was flexible and light. Besides, the ceilings were flat and comprised wooden beams and wooden decking with a thin coating of clay and soil. As a result, all our principles of earthquake-resistant construction were observed.

There are several words left to be said about the town citadel walls. The walls were 12 m wide at the footing, maybe a bit less wide at the top, more than 10 m high. These dimensions point to the fact that the walls were trapezoidal in cross-section to ensure stability. The wall was faced with burnt bricks and its core was most probably air-dried bricks. The wall was supported by huge towers. All these measures ensured high seismic stability of these defensive works, the more so as they stood on high stages (platforms) [7, 8].

We have quickly familiarized ourselves with the antiearthquake measures of very ancient builders. Now we shall take caravan pathways run from the enigmatic Harappeans to mysterious Sumerians.

Sumer-Babylon Valley between the Tigris and Euphrates

Revealed to us are low-lying plains of Mesopotamia which become marshy closer to the site where the Tigris and Euphrates flow into the Persian Gulf. From the 7th to 4th millennium B.C. in this region the primitive commune disintegrated with origination of the class society.

At the beginning of the 3rd millennium B.C. small states arose in the Sumer area, the southern part of Mesopotamia. Further, the process of state consolidation took place with formation of the so-called despotic monarchy. In the 24th-23rd centuries B.C. the political supremacy was transferred to the Akkadian kingdom situated in the central areas of Mesopotamia. At the beginning of the 2nd millennium the kingdom of Babel arose, and at about the same time the Assyria state developed in the northern part of Mesopotamia. The further history of this region saw the continuous struggle between Assyria and Babel, until at the middle of the 6th century B.C. Babel and the whole of Mesopotamia were seized by the Persians. By the end of the 4th century B.C. the Persians were defeated by Alexander the Great.

Here, in the continuously falling apart and consolidating states shaken by military conflicts the writing language, literature, mathematics and astronomy, natural sciences and arts originated, and what is most important to us, the construction practice. Achievements in these fields rapidly moved to the West and East, the cradle of human knowledge and science. There is something funny in our attempt to examine a minute part of the versatile civilization that existed for a few thousands of years in order to know what had been done by the Sumerians, Akkadians, Babylonians, Assyrians with a view to improve the earthquake resistance of their buildings. Certainly, they had to think about it.

Not in vain the famous Gilgamesh Epic tells about a local observant and industrious citizen, Noah by name, who saved his family and his cattle from a seven-day inundation caused by a tsunami wave that came from the Persian Gulf and was intensified by a fair-wind water pileup. Most probably, the Flood legend in the Bible is described on the basis of the Gilgamesh Epic. In any case, it contains an account of a flood that is very similar to the biblical story of Noah. If Noah's Ark were considered from the standpoint of earthquake-proof construction, and now we shall consider everything from this standpoint, we shall realize that it was a structure resistant to earthquakes. Noah's Ark was built on land frequently shaken by earthquake shocks that were forerunners of the shock at the bottom of the Persian Gulf, which produced a tsunami wave. Those forerunners were warnings of Our Lord to Noah making him build his ark. Noah's Ark withstood the land shocks of earthquakes and survived through wave shocks. This is accounted for by the ark's thought-out design. The ark was made of wood—light, flexible and firm material—and was a rectangular spatial framework sheathed with boards (Fig. 9). To ensure rigidity and strength, this structure was connected with a long (300 ells) wooden barge which was also a wooden framework sheathed with tarred boards. The result was a light, strong and flexible structure that obeyed all rules of symmetry and principles of seismic stability. It may even be said that Noah's Ark had seismic insulation, since it could freely slide with respect to the ground moving during an earthquake.

Fig. 9. Antishock design of Noah's Ark

Now, from legends we shall proceed to real structures.

The basic construction materials available in large quantities on the territory of Mesopotamia were clay and mineral pitch (natural asphalt). Lead, tin and iron were found in the north of the country. Stone and wood were also available from these mountainous regions. There was shortage of wood, and this affected the architecture of Mesopotamia. Vaulted ceilings of brick were used instead of flat wooden ceilings. Note that the burnt brick found wide application at the turn of the 4th and 3rd millennia B.C.; the technology of its production originated in the East, somewhere in the depths of Asia. Universally use was made of air-dried bricks made by simple drying of shaped bricks in the hot sun of south. Clay and asphalt were utilized as a mortar joining bricks. There were cases of using a lime mortar and a mortar of lime and ash. Note that clay and asphalt are ductile and flexible and, when used in sufficient amounts in a mortar, they impart the same properties to the building.

Of all the structural methods in the construction work in Mesopotamia, which may be termed aseismic, the construction of man-made stages under individual structures and whole towns comes to the forefront. The most ancient small brick building known in Tello, which dates back to about 3000 B.C., was already built on a stage. What was the objective of making such stages

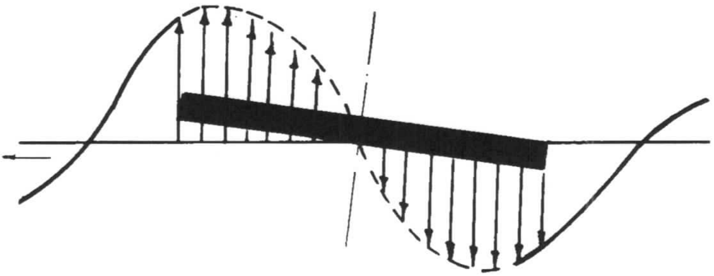

Fig. 10. Structure stage size versus earthquake wave

(platforms)? It was not in vain that huge volumes of additional construction work were done to build those platforms. The point was bad grounds between Tigris and Euphrates. While, as we shall see later, the Greeks and Romans took away bad alluvial soils and laid the foundations of their buildings on bed rocks, the builders of Mesopotamia could not do it, since mellow soils were deposited at a great depth. Knowing the importance of a good homogeneous base for a building, and the more so for an earthquake-proof building, they made an artificial base as gigantic platforms to allow buildings to be carried by weak grounds. These stages also protected buildings against floods.

A stage of remarkable design, 32 × 25 m in size, was built about 3000 B.C. under a temple in Tell'-el'Obeid. The stage carried by a stone foundation was laid of baked bricks. Bitumen-impregnated mats were put between courses of brick. Because of a comparatively small size, it would be more correct to call this stage merely a base for a building. The examples of real stages will be presented later. By real stages I mean large-size structures whose dimensions are comparable with the length of surface earthquake wave (Fig. 10). In this event, motions conveyed from the ground to the building during an earthquake are reduced at the cost of their reflection, partial damping in the body of a platform, and at the expense of equalizing, averaging and cutting off peaks by the platform itself as a very heavy large-size body. Small platform, undoubtedly, features some aseismic effects of a large platform, but in this case the structural features of a specific platform should be taken into consideration. The above-mentioned

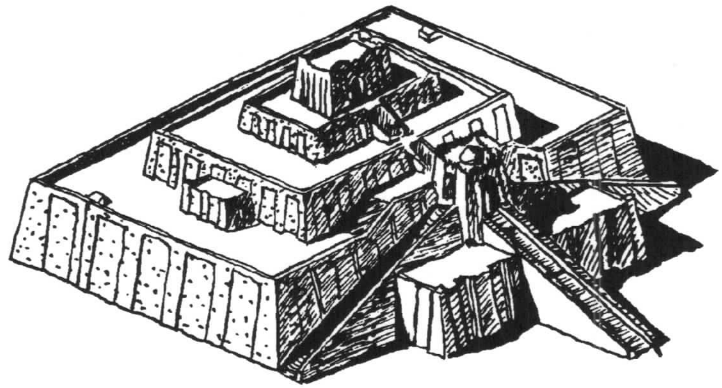

Fig. 11. Ziggurat in Ur—temple stage-base

platform (stage) in Tell'-el'-Obeid has a stone foundation. It is actually a stiff screen for reflecting earthquake waves. Earthquake motions that remain in the platform body are dampened by its laminated structure consisting of stiff bricks and soft bitumen.

A gigantic platform is expensive, but reliable antiearthquake measure. This was known and used by many builders of the past. These stages (platforms) are encountered not only in Mesopotamia, but also in Egypt, China and Mexico. A remarkable historic architectural monument of the Sumerian Age is represented by the ziggurat of Ur-Nammu built at the end of the 3rd millennium B.C., in a holy site, the city of Ur. It is erected on a vast truncated pyramid (platform), 43 by 65 m in plan and 15 m high above the ground (Fig. 11). The core of the ziggurat is of air-dried bricks laid on a bitumen mortar; it is faced with burnt bricks. In this case, we encounter the design of a platform that somewhat differs with the above-described platform of burnt bricks. A very thick platform of air-dried bricks, which is often mixed with straw, works as a gigantic pillow dampening shocks of the underground element conveyed to the building. In this case the structure itself is a soft man-made hill with slopes protected against sliding.

Platforms were made under temples, palaces and even towns, as was the case with the Mohenjo-Daro city in the Harappa. The platforms were multifunctional. They could be used for defence purposes, to deeply impress religious persons or citizens when they approach the temple or palace, and at the same time to form a reliable foundation under a structure, to be protected against floods, and, finally, to perform antiearthquake functions.

Later, in the 1st millennium B.C., still greater platforms were constructed in warlike Assyria whose architects continued and developed the construction traditions which formed in the states that had previously existed on the territory of Mesopotamia. The city of Dur-Sharrukin, the residence of king Sargon II, was built only in six years (712-707 B.C.). The city was surrounded by 23 m-high walls which were as thick. Even this ratio between the height and thickness of walls points to the earthquake resistance. Besides, the walls were shored up in a counterfort manner by 167 towers built at 20 m-intervals. The bottom of the walls was laid of stones to a height of 1.1 m. This combines a strong foundation and a stiff screen reflecting earthquake waves. The top of the walls was laid of air-dried bricks. According to the Mesopotamian construction traditions, the non-burnt bricks were to be made of clay and straw and laid on mortar from asphalt and the masonry reinforced by wooden sleepers. There is no need to comment on the ability of such a wall to withstand shocks of battering rams and underground element.

The most interesting for us in Dur-Sharrukin is the fact that the citadel, in which the temples, houses of courtiers, and the palace of Sargon were located, was laid out on a stage about 100 000 sq meters in area and 14 m high. The stage was built of air-dried bricks and faced with huge stones weighing up to 14 tons. The draining channels and ventilation holes were provided in the solid bulk of stage and ziggurat clay. A vast amount of dry ductile clay enclosed by a stiff stone holder served as a good seismic insulator for all structures of the palace complex. Willy-nilly one has to admire the ability of ancient builders to think over the details of their structures. Here you are. After building the stage and making a ductile and homogeneous base, the builders did not erect the building walls directly on the stage material. They first laid stone slabs along the entire perimeter of the walls and only then erected the brick walls on them. As a result, the building was as if floating in the elastic-plastic body of the stage. If this method of antiearthquake protection were further improved, a large pool would be dug, filled with a viscous liquid, say with fruit jelly or mazut, at least with water, and a building, like Noah's Ark, set afloat in it. This will provide ideal seismic insulation, and earthquake waves will not affect the building.

There existed stages of quite another type, rigid stages. Running a little ahead, the court complex of the Persian king Darius (521-486 B.C.), built in the new capital of Persepolis, may be considered as an example. These palace structures were built on a rigid stone stage. To build it, the builders partially used a natural rocky ground, completing it on the valley side with stonework of large dressed blocks of strong limestone. These blocks were dry-laid without mortar and were secured to one another by metal cramps. The stage had huge dimensions: 450 by 300 m in plan and up to 18 m high. An air-dried brick wall, up to 5 m thick, was erected along the margin of the stage. The court palaces were crowded inside. The earthquake resistance of the rigid stage somewhat differs from that of the ductile (soft) stage described above. First of all, the heavier rigid stage better reflects the earthquake waves. Its earthquake wave smoothing effect is also higher, but there are no damping and shock-absorbing effects. If this method were to be made absolute to provide earthquake protection, one would have to build an absolutely firm stage of mammoth weight with a size comparable to the length of earthquake wave, i.e. from 100 m to 1.5 km. If this platform is absolutely rigid, the ground under it is softer in any case, and the stage will reflect and flatten out all seismic motions of the ground under it. Everything carried by such an unfeasible imaginary stage will be protected against earthquakes. The above-described stone stage of the king Darius is certainly far from giving absolute protection, but ensures a high antiearthquake effect. Even a reinforced-concrete slab laid under a present-day building that slightly exceeds its dimensions in plan produces a fairly essential effect. Stone fragments of palaces (Fig. 12) and individual slender columns up to 20 m high remaining from the ceremonial halls stand on the stage of Darius to this day.

After considering in detail the stages on which the inhabitants of Mesopotamia built their towns and structures, we shall discuss

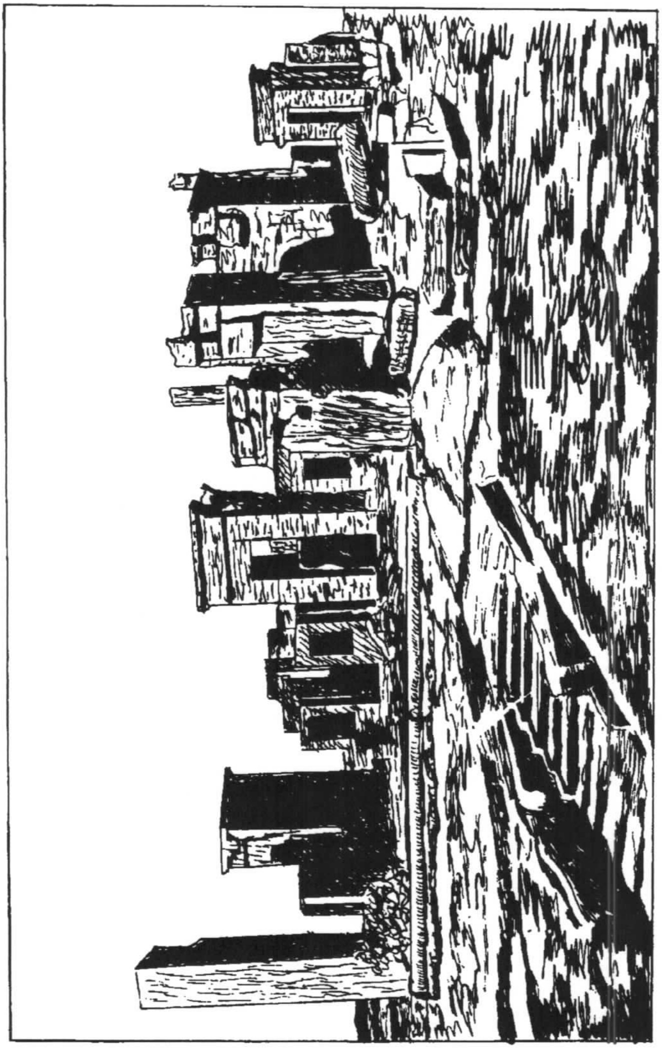

Fig. 12. Stone structure skeletons on stage of king Darius

other antiearthquake measures they took. Let us start with the stone fragments found on the stage of the king Darius (Fig. 12). These are the saved stone parts of palaces built on the stage, while the walls built of air-dried bricks and wood-reinforced have not survived. Door and window apertures, and wall crossings were made of heavy stone structures that were also used as supports for thick air-dried brick walls. The soft ductile medium was as if reinforced by stiff cores. This combination of structures with different rigidity will be encountered more than once in the history of earthquake-resistant construction, since no resonance phenomena can occur in these combined systems. The ductile elements prevent resonating of the rigid elements and vice versa. The stone cores were installed observing a series of antiearthquake measures. This, first of all, includes thorough fitting and dressing of stone blocks and their joining by metallic cramps without mortar. The stone blocks were placed so as to avoid off-center loading and thus to eliminate tilting moment. The following structural method is of interest to us. A layer of gravel was put under the columns, pylons, and door casings installed on special stone slabs in order to provide the uniform pressure distribution under these constructions. Similar measures will be frequently encountered by us later. All this is in compliance with the above-mentioned principles aimed at preventing nonuniform loads of the structural elements. As to the air-dried brick walls, their resistance to earthquake has been discussed before. The brick, which is made of clay mixed with straw, well dried in the sun and laid on a clay or bitumen mortar forms a homogeneous solid mass with elastic-ductile properties. Moreover, this mass is supported by brick counterfort projections and stone cores. There are still other structural elements on which the strength of the whole structure depends. Fig. 13 shows a very quaint head of column, which decorated large reception halls. From the structural viewpoint, this column head is very suitable for placing a ceiling beam of cedar of Lebanon (*Cedrus libani*). One may be sure, a beam thus fitted will not come off the column during an earthquake.

Now, let us return somewhat over the time river to visit the very centre of Mesopotamia, the famous Babylon. In this site the Tigris and Euphrates mostly approach each other. Consider the construc-

Fig. 13. Heavy-duty head of Assyrian column

tion techniques used in the most studied New Babylon Kingdom which was founded by king Nebuchadnezzar II in 605 B.C. Babylon was seized and fully destroyed in 689 B.C. with flooding the city territory by the Assyrian king Synahherib, while his son, king Asarkhaddon, ordered to fully restore the city according to a unified plan. At the time of the Babylonian king Nebuchadnezzar II they continued to construct, decorate and fortify the city. All three wonders of the world were situated in this locality. You, probably, know that the present-day set of seven wonders of the world includes: (1) the pyramids of Egypt, (2) the Hanging Gardens of Sammuramat, (3) the temple of Diana (Artemis) at Ephesus, (4) the huge ivory and gold statue of Zeus, (5) the colossus of Rhodos, (6) the mausoleum of Halicarnassus, (7) the Pharos of Alexandria. All these wonders of construction skill were someway connected with earthquake effects, and we shall talk about all of them. However, in the past there existed other sets of seven wonders of the world. One of such sets included the walls of Babylon. The double row of walls built at the time of king Nebuchadnezzar II made the city an unassailable fortress. The walls were built of burnt and air-dried bricks laid on a mortar from asphalt and rush. The outer wall was 8 m high, 3.7 m thick, the inner wall was 11-14 m high and 6.5 m thick. The geometric ratio of wall height to wall thickness was about 2:1; wall support by counterfort towers, plus the ductile properties of the structure material, made the walls sufficiently earthquake resistant.

Another set of world wonders included the Babylon tower instead of the defensive walls of Babylon. This is the ziggurat of Ethemenank. The name means "house coupling Heaven and Earth" (in the Sumerian). Certainly, this ziggurat was ruined in Babylon destruction in 689 B.C. The Assyrian king Asarkhaddon restored the tower, while the Persians, after the seizure of Babylon, began destroying it. Alexander the Great decided to restore the ziggurat and ordered to raze its remains to the ground. However, he had no time to start its construction anew. The result is that no other traces of the really existed Babylon tower can now be found, except for the description of ancient authors. According to these data, the square ground tier of the ziggurat was 90 by 90 m in plan, 33 m in height. The core of this tier (60 by 60 m) was made of air-dried bricks. The core was faced to a thickness of 15 m by burnt bricks. For stability, the facing walls were slightly inclined inward and had counterfort projections. This gigantic ground tier served as the base for the subsequent, gradually decreasing in size, much smaller six tiers, like in the above-described ziggurat in Ur. The next tier was 18 m high and five more tiers, each 6 m high. The construction of these tiers was the same as that of the ground one, i.e. a soft core with more rigid facing. The 7th 15m-high tier, the shrine of God Marduk, was, probably, wholly built of burnt brick faced with blue tile. The total height of the ziggurat was about 90 m. From the standpoint of earthquake resistance, the design idea in this tower is very interesting and perfect. First, it is geometrically harmonious, has similar height and width, and pyramid-shaped outline with a low centre of gravity to ensure stability in shaking processes, if any. Second, we again deal with two component elements of the structure: ductile and plastic on the one hand, and less ductile on the other. The bulk of plastic clay fills an enclosure of burnt brick. Note, in order not to affect the homogeneity of medium and cause nonuniform settlement anywhere in the tower, its internal body has no void spaces for rooms, stairs and the like. Any shaking and wave processes will be dampened within this Babylon tower, and the temple of God Marduk on its top will be protected against all outrages of earthquakes. From the present-day viewpoint, this is a real earthquake-insulated temple.

Now, about the third wonder of the world related to Babylon, about the Hanging Gardens of Sammuramat. According to one of the legends, Sammuramat was the wife of Nebuchadnezzar II. It was for her who came from the mountains of Midia that these

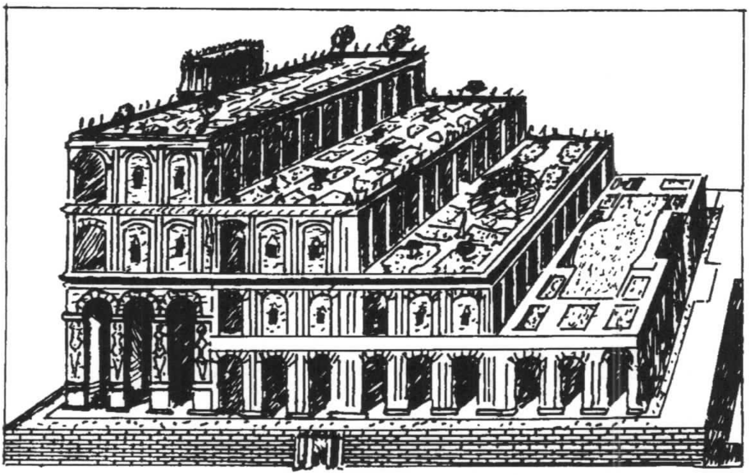

Fig. 14. Hanging gardens of Sammuramat

hanging gardens were built so as not to miss much her beloved mountainous landscapes. The well-to-do people living in that hot climate had a custom of building small oases on tops of their houses. Certainly, the king of Babylon could take the liberty of building such gardens for his beloved wife, so that we now rank them among the seven wonders of the world. The only thing unknown is why these gardens were called "hanging". Perhaps, it was to influence our imagination still more. In fact, these legendary vast gardens were standing in a most prosaic manner and had solid foundations that were revealed by archeologists in our times. We shall have an opportunity of encountering really "suspended" structures.

What was the construction of these "hanging" gardens of Sammuramat whose erection required the entire arsenal of construction techniques of that time? Referring to the reconstruction (Fig. 14), the gardens were a four-level structure with two walls common to the palace building. This is certainly a cost-effective practice, but it is wrong from the viewpoint of earthquake resistance: this affects the principle of symmetry, because two buildings of different rigidity are coupled together. It was necessary to provide an aseismic joint-clearance between the independent walls of each structure. The basic building materials of the structure were different types of brick and stone. Note that stone was used in construction mainly in Assyria. In Babylon its use commenced only in the Newbabylonian period in most important structural elements such as foundations and frameworks of various apertures. The basic material was brick whose main bulk was represented by sun-dried bricks. Due to scarce fuel in Mesopotamia for the production of baking bricks, the burnt bricks were used only in important structural elements. The burnt rectangular brick was utilized for facing which supported barrel vaults built of special wedge-shaped bricks. Segment-shaped bricks were employed to erect round columns. As was already mentioned, the wide use of vaults in Mesopotamia was apparently aimed at saving wood material. However, then, at the dawn of construction skill, only small span barrel vaults without mutual crossings were made. The walls were sufficiently thick to take up thrusts produced by these vaults. It was then that three-layer walls appeared whose various structural implementations we shall encounter many times on the pages that follow. The three-layer wall used in Mesopotamia consisted of outside facings laid of burnt bricks so as to provide a bond to its bulky internal core made of air-dried bricks. Bitumen and clay were used as a mortar. As you know, these ductile walls were sufficiently resistant to earthquakes. All the above-mentioned construction methods conventional for Mesopotamia had found their use in the construction of the gardens of Sammuramat. Each tier was ceiled by heavy barrel vaults. Laid above the second vaults were large stone slabs, then courses of brick, bitumen, lead, and finally a thick layer of soil in which tall trees could grow. As you see, the load is enormous, and this was well understood by ancient builders. Therefore, the structure was reinforced by implementing a structural element seldom encountered in these localities. To support the vaults, thick stone pillars of tier height were used, which were made of cut stones connected to each other by metal dowels sealed with lead. All vertical load was conveyed to these stone pillars as supports more rigid than the brick bulk laid on the bitumen or clay mortar. This ductile brick bulk served as a supporting and earthquake-insulating medium for the load-carrying stone pillars. The joining of stones by metallic elements sealed with lead was an antiearthquake method well-known in Greece, and we shall talk about it later. The reinforcing of brickwork by wooden spacers was a purely antiearthquake method here, in Babylon. We do not know when and why the gardens of Sammuramat ceased hanging, or rather standing. Most likely their destruction started with the bulk of short-lived air-dried bricks going to pieces whose function was to support more rigid and strong load-carrying elements of the structure. The worse air-dried bricks deteriorated, the higher was the probability of the structure collapse. And once, most likely during an earthquake, the legendary standing gardens of Sammuramat saw their end, and Sammuramat herself might be a very beautiful and wide Queen of Babylon, rather than the wife of Nebuchadnezzar II. In any case, in 325 B.C. Alexander the Great found these gardens safe and sound, and it was here where he terminated his brilliant campaigns. Under the vaults of the gardens of Sammuramat Alexander the Great wanted to find bracing freshness to recover his health. It was here, in a palace adjacent to the gardens, where Alexander the Great took his leave of warriors.

There is one more important requirement for the earthquake-proof construction of which I have not yet spoken, but of which the builders of Babylon were well aware and the observance of which was checked by the kings themselves. This was the requirement for the high quality of construction jobs. The brick ought to be neatly shaped and well burnt, stones tightly fitted to one another, mortar strong, and wood dry. Judge by yourself, of 282 clauses of the laws issued by the famous Babylonian king Hummarabi (died 1750 B.C.) who talked about himself: "my words are splendid, my wisdom is unequalled" and who actually had a good understanding of good management, at least five clauses were dedicated to the quality of construction. I cannot help quoting the three of them.

If a builder builds a house for a man, does not make its construction firm and the house collapses and causes the death of the house owner—that builder shall be put to death.

If a builder causes the death of the owner's son, the builder's son must be put to death.

If a builder builds a house for a man, makes its construction flimsy and a wall falls—that builder shall strengthen the wall at his own expense.

It is interesting to look at a builder who would disobey these stern directions and would carry out his construction job badly. Four thousand years ago, his construction career would come to an end in no time. Nowadays, he may continue his bad work under no pain of severe penalties.

In a way, I feel sad to leave this wonderful Babylonia where so many masterpieces of construction skill were erected and served as prototypes for future builders. What a wonder the brick and stone bridge across the Euphrates is! The piers of the bridge are built of large cut stones joined by the same metallic cramps, and burnt clinker bricks were used to build barrel vaults to span the spacings between the bridge piers. The clinker shape of brick also protects the vaults against destruction under earthquake conditions.

To continue our stay on the picturesque plains of Mesopotamia that are rich in ancient construction traditions, let us make an excursion to the time of the existence of Persia which directly continued the Assyrian state. The more so that we have already talked about the stone stage on which the court complex of the Persian king Darius I was located, in the capital of Persepolis founded by him.

In 615-605 B.C. Assyria was destroyed by Midia which in turn was defeated in 553 B.C. by the Persians headed by king Cyrus II who founded the dynasty of Achaemenids. According to the division adopted, the most ancient period of Achaemenids commenced. It ended in 330 B.C. when Alexander the Great defeated the Persians. With his death and disintegration of the empire founded by him in Mesopotamia, the Seleucid dynasty came to power. Their state, however, turned out to be not strong, and in 250 B.C. the kingdom of Parthia was formed. The second, Parthian period of Persia began, when the Greek-Roman traditions and methods prevailed in the construction technology. The time during which the Sassanid dynasty (226-636) reigned was called the third period that ran as struggle against foreign influence to recover local traditions. Let us consider several examples of architectural monuments related to each of the periods.

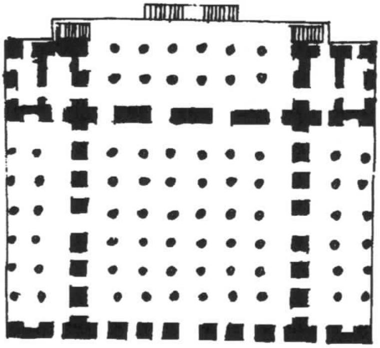

Fig. 15. Large reception hall of king Xerxes

We have already talked about the stone stage of the king Darius and the stone fragments and columns standing on it that are related to the Achaemenid period. Now, more detail about these columns. The latter are remains of the vast and tall royal reception halls, the so-called apadana. For the first time here the Ancient East saw the use of monumental architecture for building high society structures. Till that time, it existed solely for worship purposes. Of all wonderful and magnificent reception halls, we shall consider the apadana of Xerxes (Fig. 15) which was 62.5 m by 62.5 m in plan. The height of stone columns in the porticos was 19.5 m, the column diameter being 1.58 m. The columns inside the hall were 18.0 m high. The structure stood on an auxiliary stage, 4.0 m high. These were practically the highest and well-proportioned stone columns in the world. The column-to-column span equalled 8.75 m, which was extremely large for that time. The design of the entire apadana, in which free space was fought for without compromise, can be seen in Fig. 15. The walls in it, as it should be, were built of air-dried bricks reinforced with wood and strengthened by stone cores. The ceiling was sufficiently light, wooden, with soil filling to allow such tall and thin columns to be erected since the load they carried was small. From the standpoint of earthquake resistance, both the light ceiling, made of elastic and tough material, and its design were important. And the ceiling was the result of qualified workmanship. The ceiling beams were arranged longitudinally and crosswise, tied to one another and to the walls and columns. There was a wooden decking with clay coating on the top. A single ceiling-closed system was formed that comprised columns and bulky walls. The columns, as they should, carried the vertical load, while the walls, in case of earthquake, took up the horizontal load. Many of such logically founded multicolumn structural designs will appear in subsequent centuries, but that in question is one of the first. The high construction skill is indicated by the fact that of 72 well-proportioned, like trees, columns of the apadana of Xerkes 12 columns have survived till now. The wooden components decayed, while the air-dried bricks were weathered.

My thoughts were completely disturbed by the just described structures of the Achaemenid period, after I acquainted myself with them. The stage, walls of air-dried bricks are traditional. But who dared erect such thin and tall stone columns? The Greeks made columns at least half as long. Where are the prototypes of these columns? In the construction matter gradualness is important. A simple structural element was invented and gradually improved to perfection with experience. Two stones leaned against each other and placed above an opening made in a wall gradually changed into a strong heavy arch through evolution. To ensure this evolution, conscientious, painstaking and even wise performers were needed. Industrious apprentices were not enough for real progress, there was a need for highly educated people of unique thinking who could take the risk. Those were persons who would dare use two inclined stones as a vault, similar people would dare perform an operation on an open heart. The apadana of Xerxes appeared before us at once as a perfect structure with nothing to be taken away from, or added to. The proportions of the ancient stone column were the same as those of the modern reinforced-concrete column. I am not sure that a modern designer would make up his mind to plan such a column for a seismic area. It is a mystery how the ancient builder could allow for the strength properties of materials in a construction. I have no doubt that he could do it. I will do my best to relate to you the stories of structures that are either a masterpiece, or as in the case with the apadana of Xerxes suddenly and brilliantly arise to cause an unexpected leap in the development

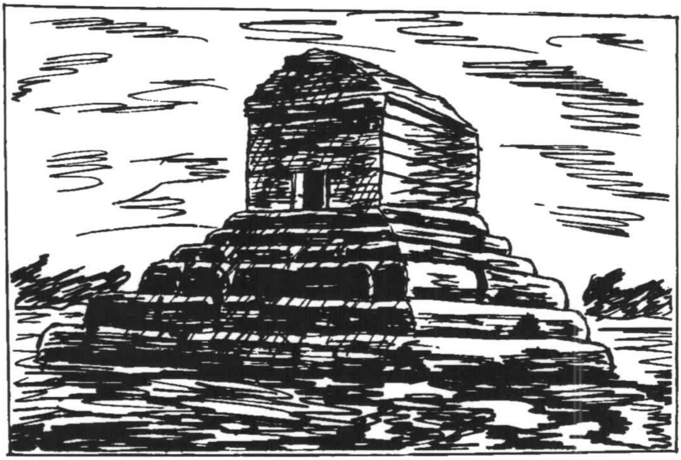

Fig. 16. Pyramid-like tomb of Cyrus the Great

of construction skill. There is one more thing to tell you. We consider the material history of the earthquake-proof techniques invented by ancient builders, which is based on real facts from archeology and history of architecture. However, there is other than material history—an example is the history of ancient religions. We shall never know what Marduk and his priests were doing on the top of the ziggurat five thousand years ago with their and somebody else's wives, and whether they had wives at all, but excavations helped us to know the construction of the ziggurat and we could build it. Our material history is more authentic and to my mind better depicts the ancient man as a builder with his diligence, courage, information content, and breadth of mentality.

There is one more example taken from the architecture of the Achaemenid period. At present we shall not speak of the tombs cut in rocks, though they were built here at that time, and there is something to discuss from the viewpoint of earthquake resistance. Now we shall consider the unique tomb of king Cyrus (Fig. 16) built in the 6th century B.C. A six-step high stage carries one more, the 7th step, which is a small rectangular (3.16 × 2.18 m in plan) burial chamber with a gable roof. All elements of this burial-vault are made of large limestone blocks. The pyramidal stage (base) consisting of step slabs whose thickness decreases with stage height imparted to this tomb the strength, stability and longevity to withstand earthquakes for more than 25 centuries. If we check the tomb of king Cyrus for our principles of earthquake resistance, we shall see that all of them are observed: the symmetry, low centre of gravity, rational dimensions, the total height not exceeding 11 m, the closed contour of each step, overlapped bulky stone blocks connected with metallic ties, except for, perhaps, weight lightening. Superheavy structures and their behaviour during earthquakes will be discussed later, when we reach Egypt. To the point, the tomb of Cyrus copied the pyramidal shape of the ancient Iranian shrine, and generally, the pyramidal shape ensured seismic stability of the structure. The same shape was traditional for many ancient buildings. Recall the ziggurats we discussed. Now a tomb is under discussion, and further there will be pyramids, stupas, and the like.

An example will now be presented from the history of architecture of the Pathian period in Persia. We shall not dwell upon this intricate period in more detail. At that time structures were popular that resembled in shape the Greek and Roman ones, but inasmuch as the East itself was known for construction traditions, the structural implementation of those seemingly Roman buildings was made in an eastern manner. These hybrid structures will be discussed when we reach the Caucasus, whereto, as to Central Asia, the Parthian kingdom extended. My example is as follows. At the very beginning of our talk about the Sumerians, when I started telling you only about the brick platform (stage) on a stone base, dated to 3000 B.C., I could mention a wonderful column discovered in Tello and related to the same time. But I did not do that and postponed our rendezvous with the column till the Parthian Age. It turned out that the brick column in Tello and the column discovered in the Parthian Nice are of similar design. Note, the Parthian Nice is located in Turkmenia, 20 km from Ashkhabad, and those who visit the excavation themselves or with an excursion can see the column I am speaking about. The time distance between the above columns is hard to imagine—3000 years. These are bunches of four round columns tied to one another (Fig. 17). Each round column is laid of burnt segmental brick on

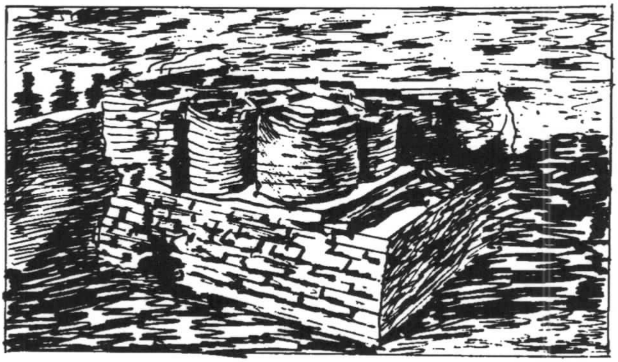

Fig. 17. Built-up brick column

clay with tier bonding, as it should be in a well-planned structure. The four-trunk column stands on a high foundation which is its bottom binding element. It is of interest to see how brick was used for the top binding of this built-up column. In any case, nobody yet has undertaken to reconstruct this assembly. Much can be said about the built-up lightened column which is strong and at the same time ductile due to the clay mortar used. It can be said how clever the builder was, and how he could follow the traditions, and what fine intuition he had, and how he knew the material, and, finally, that these columns, real springs, were devised by ancient builders most likely independently of each other, using merely the builder's logic. All this holds true, but our way is onto the next period, Sassanid.

After defeating the last king of the Arshakid dynasty in 224, Artashar I united under his power the lands of Iran and saved the Mesopotamian cities of Seleucia and Ctesiphon as the centre of the new state. This period is characterized by serious social changes: the country took the way of feudal development. Hence, the relevant consequences for the construction technology were as follows. Many towns were built as administrative centres to control vast country both for the local feudal nobility and the central government of shahinshah. More than that, each shahinshah, who ruled a powerful state capable of opposition to Rome itself, did his best to build the palace as large and magnificent as an eastern ruler can imagine. The great construction work of feudalism started. The construction jobs were carried out in a haste and on a large scale, and there was no time to prepare high-quality building materials. Use was made of non-dressed stone available. At that time dressed stone blocks were not popular. Certainly, from the viewpoint of earthquake resistance nothing good could come of it in these regions subject to frequent earthquakes. However, let us consider some details of construction work at that period. In compliance with the traditions and local conditions of this woodless country, rich in clay and stone, such structural elements as arches, vaults and domes were utilized for ceilings. These vaulted ceilings were made of burnt brick, stone and even air-dried bricks. The outlines of vaults and domes showed changes important from our point of view. These were made not only circular-outlined, but as a rule parabola-outlined, and elevated in ceilings over large spans. Evidently, it was primarily connected with job execution. They attempted to lay domes and vaults without using high-cost wooden curve pieces in a corbelling inward manner. This elevated outline of a dome decreases its thrust applied to the walls to reduce their weight and, thus, cut down the weight of the whole structure. Besides an elevated dome better stands to whatever dynamic loads, including earthquake loads. Even cracks in such a dome cannot affect its stability. This will later be illustrated by a figure. Maybe, the elevated dome was connected with the requirements for the earthquake resistance of the structure, rather than job execution?

A serious imperfection of some structures then erected was that the domes were made of rounded and quarry stone due to the lack of dressed stone (Fig. 18). First, an envelope was laid on a gypsum mortar. Then all that was filled with concrete which comprised undressed stone and the same gypsum mortar. Naturally, the resultant ceiling was very heavy. To support a heavy dome, the walls were made as heavy. One can see the difference between a vault laid of dressed clinker stones, as was the case with the bridge in Babylon, and a vault, though mortar-bonded, but laid of stones poorly fitted to one another. Accordingly, a structure erected of undressed stones was very heavy, non-uniform in strength, prone to non-uniform settlements and deformations, which often col-

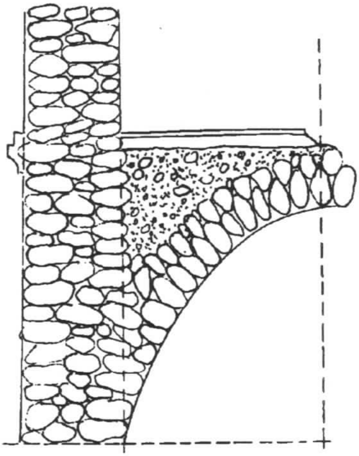

Fig. 18. Domes of rough stone

lapsed even in the absence of earthquakes. To learn how to lay a dome of rough stones is generally an achievement, but not any achievement adds to the earthquake resistance of buildings. We shall further encounter such cases. Here is another example when a new construction method was favourable for improving the earthquake resistance of a building.

At all times, when domes began to be used to provide ceilings of buildings, a problem was solved how to join a round dome to a square room below. The Sumerians tackled this problem simply. They used no domes and laid barrel vaults over rectangular rooms. The Romans erected round rooms under round domes, and if a building was to be rectangular, proper niches were added. The Persians solved this problem with the aid of the so-called arched trompes. The corners of a square were spanned by small arches not yet separated from the dome body as an individual architectural detail. The result was an octagon. Then it was easy to fit a round base of the dome to the octagon. This smooth changing over from one geometrical shape to another in a building adds to its resistance to earthquake loads.

I also want to tell you about the construction of the fortress walls of ancient Derbent in Dagestan. The Sassanid power occupied a vast territory, reaching the Caucasus mountains in the North. These mountains served as the natural protection of the Sassanids against intrusion of the northern nomads. The only hazard was represented by a narrow passage between the Caucasus mountains and the Caspian sea. Here, in the middle of the 6th century, on the order of king Khosrov I, a first-class fortress of Derbent was built to close this passage. In the Persian language the word "darbend" means "gate node". The fortress included a complex of defensive works. This first of all comprised a citadel of town situated on the hill nearest to the sea. A mountain wall that prevented the enemies from passing through the mountains ran from the citadel to the west, deep into the mountains. Two walls with many defensive towers ran about 3 km eastward from the citadel, over a plain, to the sea. Just these walls closed the passage along the sea coast. The town was situated between these walls. The town walls extended far into the sea to form a harbour and prevent turning movement by shallow waters. Part of the town walls and the citadel have survived. They looked especially picturesque when, still in the 70s, carpet fairs took place there. Bright black-and-red homespun carpets hung down high bulky walls. One could imagine himself in the 7th century, if it were not for the asphalt seen under his feet.

So, we shall talk merely about the design of the walls. Certainly, the walls that ran into the sea did not survive. They are known to be laid of stone blocks and connected by metallic cramps. The mountain walls, citadel walls and town walls of similar construction that were laid about the same time were well studied. These three-layer walls comprised external stone facings and internal rubblework made of undressed stones and lime mortar. The facing was made of fairly large slabs of dense shell rock about 100 by 65 cm in size and 25 cm thick. The facing slabs were laid so as to provide reliable bonding between the stiff facing and softer bulky core. To this end, in each tier the slabs were laid alternately stretcher-wise (with the wide side in the wall plane) and header-wise when the entire stone extended into the wall body and only its end face could be seen. Every few tiers an additional tier of bonder-lying slabs was made, as shown in Fig. 19. The walls were erected as follows. A tier of facing was dry-laid, and the space thus

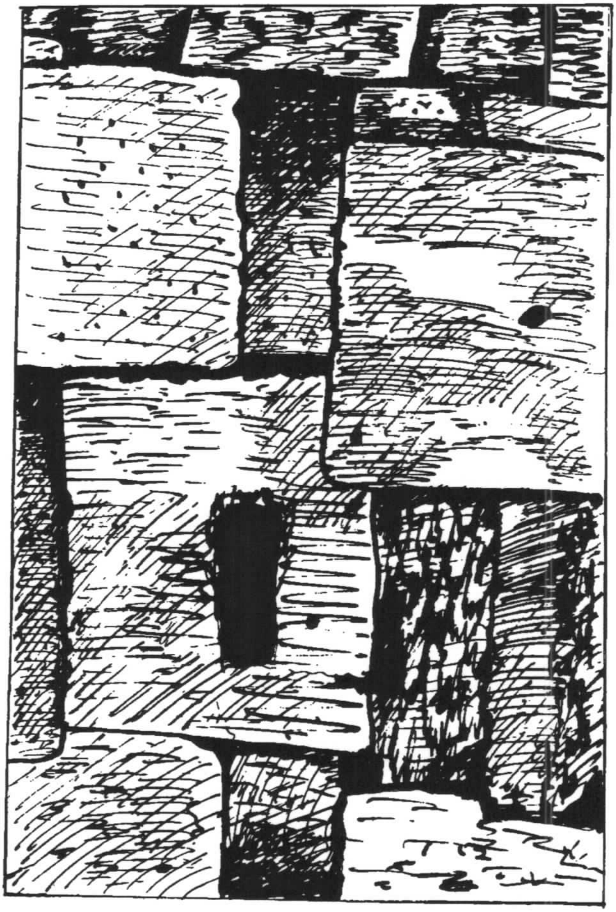

Fig. 19. Three-layer wall of Derbent

formed was filled with undressed stone; only then the lime mortar was poured in. The method of mixing the aggregate and mortar beforehand was not in practice. The result was a layered core structure, since the mortar could not get through the entire thickness of undressed stone fill. This can now be seen at places where the walls are ruined. These layered walls which had tough and ductile layers, were sufficiently ductile to meet the earthquake-

Fig. 20. Parabolic vault of king Khosrov's palace

resistance requirements. Note the dimensions of the town walls whose thickness varied from 2.3 m to 3.8 m, with the wall height up to 12 m. Those were not already walls of air-dried bricks in which the height and thickness were comparable. These walls were stronger and had another height-to-thickness ratio. In these very ancient three-layer walls in the Caucasus the major strength and deformation properties of the wall were determined by the fairly ductile core. How the earthquake resistance of these three-layer walls will reduce by our time, due to a decrease in the core thickness and deteriorated bond between the facing and the core, we shall know while discussing the history of the earthquake-proof construction in the Caucasus. It must be added in favour of the walls in question that to ensure their general stability during earthquakes, they had a sufficient number of bends in plan, as well as counterforts and towers supporting them. There is one more example, the last one, from the almost four-thousand year history of construction in Mesopotamia we have quickly passed.

An ancient architect with deep knowledge in the construction matter and unimaginable decisiveness left us the palace of king Khosrov I in Ctesiphon which is the highest achievement in vaulted structures during the Sassanid dynasty (Fig. 20). Most interesting for us in the structure of this palace are two brick vaults ceiling the central part of the palace. These vaults are almost 27 m in span, 37 m in height, and 45 m in length. The first vault shown in the figure is open at the front and forms the ceiling of the king's reception hall. There is a vertical brick wall at the rear end of this vault, which is connected with it. The second inner vault has walls at both ends.

The size of these gigantic brick arched vaults built in the 6th century will be surpassed by the Iranians themselves only in the 14th century. I wonder how the architect made up his mind and the king permitted such vaults to be erected. At that time there was no experience in constructing such large vaults. The largest brick dome on a lime mortar, which is easier to erect than a vault, was built in Chor-Kapu by that time. Its diameter was 16.15 m. Note, to save bricks, the walls of this structure were erected of rough stone, which affected the seismic stability of the structure. We are interested in the structure of the vaults above the halls of the king Khosrov palace not only because of their dimensions, but also due to the construction techniques used in that structure, which allowed at least a part of one vault to survive. Let us try to look into these techniques.

The royal reception hall ceiled by a gigantic brick vault and opened at the front was the architectural centre of the palace. The other hall ceiled by a similar vault and located behind the former along the same axis was closed by walls at both ends. Both vaults were not structurally coupled with each other, which was, certainly, correct from the standpoint of seismic stability of vaults themselves and the building. The major problem in the building, of which the ancient architects were well aware, was to take up the thrust produced by the two heavy brick vaults. Moreover, they knew that such vaults were erected for the first time and that the safety margins ought to be large enough. That was done. The wall thickness of the wall-vault smooth joint was 4 m and 7 m at the wall foot. The ancient builders believed that these bulky walls were insufficient for taking up the thrust. Then the building wings were erected in the form of vaulted and domed rooms whose walls bore against the walls of the central vaults to provide additional support to these walls. As history shows, these additional measures were superfluous. The palace wings, except for the front wall, failed long ago, while the first central vault supported merely by its walls survived. No wonder that the ancient builder was so reasonably prepared for the walls to take up the thrust caused by the brick vault, 27 m in span, 1 m thick at the voussoir joint, and 1.8 m at the vault feet where it rested on the walls. Such a vault produced a monstrous thrust by its huge weight. It is also interesting to know how the thrusts caused by vaults and domes were determined 1500 years ago, and they did it well. I intentionally did not yet mention the outline of the vaults in question. There is a surprise for you. The gigantic vaults had an elevated outline whose configuration can be described from three centres, rather than the circular barrel outline described from one centre of more ancient vaults. The elevation of a dome or vault top was a very important measure from the viewpoint of seismic stability, since it reduced the dome or vault thrust and, thus, reduced the weight of the load-bearing walls and the whole building. Though the palace was made massive, the architect who created it evidently thought how to reduce its weight. There were no coffers that were easy to form in the cast concrete technology of Rome; neither there was a thin brick shell with brick rigid ribs, because there was not yet skilled brickwork we saw a few centuries later. Instead of all this, the structure was lightened by laying the vaults of varying thickness. The vaults were thinner at the top voussoir joint and gradually thickened towards the vault feet. Besides, the structure had an elevated outline. The walls, as you also know, were of varying thickness. The result was a decrease in the structure weight and uniform loading of its material. Thus, those were the same problems we are facing today.

There is one more interesting detail in the example considered. The former vault above the royal reception hall survived, while the rear vault collapsed long ago. What is the matter? Both vaults were similar in size and shape, quality and materials. The answer to this enigma is to be found in a difference of the vault designs that I casually mentioned. The former vault that survived was more flexible owing to the absence of its front wall, while its rear wall separated from the vault. This large-span vault, not stiffened by ribs and walls, was sufficiently ductile to withstand unequal displacements of bulky walls during earthquakes. At the same time, the rear vault reinforced by bulky walls at both ends was destroyed. In compliance with our principles of seismic stability elastic structures behave better than rigid ones during earthquakes. Generally speaking, buildings in the Sassanid dynasty time had heavy domes, vaults and walls, all structural elements being rigid and, especially walls, non-uniform in their strength [5, 6, 7, 9, 10].

That's all, we have had enough of biblical plains of Mesopotamia. On, to the valley of Nile, to the third great river civilization.

On to Nile Pyramids and Temples

Of the entire diversity of Egyptian civilization architecture I suggest to consider three objects. This is first of all Egyptian pyramids known as one of the world wonders and constructed during the time of the Early Kingdom in the first half of the 3rd millennium B.C. Then there are mighty temples built in the New Kingdom (the 16th–11th centuries B.C.), plus one more wonder of the world—the Pharos of Alexandria built in the 3rd century B.C. under the Ptolemies who founded a state with the capital of Alexandria situated in the valley of Nile. This state arose after the disintegration of the power of Alexander the Great.

Let us start with the pyramids. I do not know how you see ancient Egypt, but I see it as great floods of the Nile river whose flood waters carry mud and silt to renew the fertility of fields, and mummies embalmed in the ancient Egyptian manner and buried in the ground or immured in gigantic stone pyramids, and very large multicolumn temples from the roofs of which shaved priests observe the motion of planets and peoples. Over wide, ideally straight roads groups of Egyptians are moving on rolls the multiton rectangular stone blocks towards pyramid crystals seen far away. The abundance of stone available in diverse types served as the material basis for the development of the Egyptian monumental architecture which started simultaneously with origination of the Egyptian statehood.

A huge multistep stone pyramid of Joser, 60 m high and 109 by 121 m in base was built by 2800 B.C. This pyramid still stands under conditions of fairly high seismic activity in Egypt. Looking at this most ancient pyramid and other improbably heavy Egyptian structures, the first thought that comes to your mind is that their weight contradicts one of the basic principles for earthquake-proof construction, i.e. the weight reduction. It seems that this principle was not simply ignored in the Egyptian monumental structures, but, most likely, these structures were specially made as heavy as possible, in defiance of this principle. Herein you will not find voids in the structure, or light fillers aimed at reducing the weight of a pyramid or temple. These structures, however, existed during several millennia in the earthquake-hazard area. What is the matter? May not the structure weight be reduced? It does have to be reduced! It must be borne in mind that the weight-reduction principle applies to structures of moderate, normal, so to say, weight. But other laws become effective with enormously heavy Egyptian structures. Most important here is the factor of interaction between the ground shaking during an earthquake and the immense mountain mass lying on the ground. This interaction reduces the effect of an earthquake, and the superheavy structure does not undergo displacements and accelerations, as the case might be with a light building erected in the same site. Physically it can be seen on the snake-like dragon model given above. The earthquake dragon simply is not strong enough to badly shake a superheavy structure. It comes out that the heavier and stiffer the structure and softer the ground under it, the more reduced is the transmission of earthquake shaking from the ground to the building.

Superheavy structures have survived not only in Egypt. Cyclopean dolmens mentioned above, more ancient than the Egyptian pyramids, have survived in the Caucasus known for high seismicity. Moreover, when studying Greece and considering the central part of the tomb of Atreus, we find out that it has a side chamber ceiled by only two stone slabs of which one, 8 by 5 by 1.2 m in size, weighs more than 100 tons. Despite the weight, these structures have well survived. We shall encounter other enormously heavy, but antiseismic structures.

Now you see that the creation of superheavy structures is a possible trend in erecting the earthquake-proof buildings. But most of architects, however, preferred and prefer today to erect light buildings, which is more simple and cost-effective.

As the next step, let us consider some structures of Egypt from the standpoint of the weight principle used in them and analyse how the enormous weight of a structure ensures its integrity and monolithic nature instead of cement mortar and, thus, adds to its seismic stability.

Let us talk now about the pyramids. These huge geometrically harmonious structures, which are perfect in design and make and have every detail thought out, display automatic seismic stability. It was not in vain that the pyramids are one of the world wonders, and this is the second wonder this book deals with. Even from our viewpoint this is a wonder, since almost five thousand years ago nearly all principles of earthquake-resistant construction were implemented in the pyramids. Really, the pyramids are ideal in geometrical shape, as to the earthquake resistance. Their centre of gravity is low, respectively. Certainly, the contours in all directions are closed. The stones are thoroughly fitted to one another and clamped by the above tiers. The only principle that is not observed is the weight reduction requirement. Not we are to blame them for this. We ourselves have not yet got a good understanding of the interaction between the structure and the ground during an earthquake. In any case, their approach to building the earthquake-proof structures on the basis of the weight principle has been confirmed by the historic experience. The pyramids and temples are still standing. It should like to see myself and show you the records of an earthquake obtained simultaneously on a pyramid and somewhere off it on the ground. I have not found such records, and I do not know whether there are any. But to my mind they would differ much, accelerations by the pyramid records would be far less than those taken on the free ground.

An example is a very famous pyramid erected by pharaoh Cheops (Fig. 21) in the 26th century B.C., at the time of the Old Kingdom. This is the most ancient and largest pyramid in Giza. The Great Pyramid of Cheops measures 233 m in side with an original height of 146.5 m. This pyramid is laid of thoroughly dressed and tightly fitted lime blocks to guarantee uniform loading of the material, strength and homogeneity of masonry. The pyramid lime blocks weigh from 2.5 to 30 tons. The maximum block height is 1.5 m, near the base of the pyramid. The top blocks are 55 cm in height. This step gradation ensures the stability of the pyramid structure. Try to do just the opposite, drag large stone blocks to the top and lay the base of small stones, and your

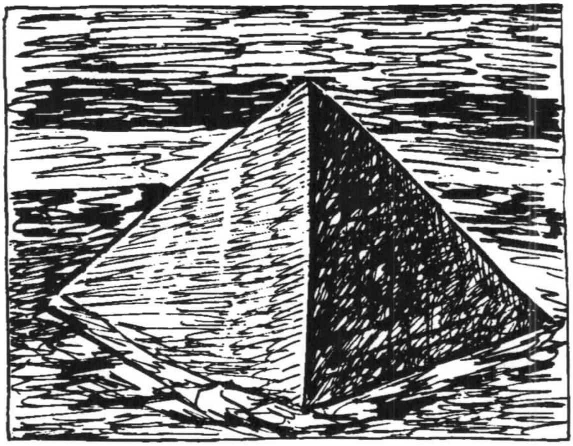

Fig. 21. Stable form of the Great Pyramid of Cheops

structure would go to pieces. To provide superweight and uniform properties of the structure, the pyramid, except the burial chamber and galleries, has a solid masonry (Fig. 22). The stone blocks are laid without mortar which is unnecessary because of their size and weight. Besides, the blocks are tightly fitted to one another. On the outside the pyramid is faced with plates of ground limestone.

To sum up, an analysis of the pyramid construction from the standpoint of earthquake-resistance principles shows the following: mass and rigidity are distributed uniformly, symmetry requirements are met, the centre of gravity is lowered, the masonry is strong and uniform. Moreover, there is even ductility to make possible shifts between blocks. The geometrical proportions between the dimensions of the Pyramid of Cheops are very curious and reasonable. The square of its height is equal to the area of the side face which is an equilateral triangle. The physical picture of this ratio appears in Fig. 23. The area of a square having a side equal to the pyramid height equals the area of the inclined triangle. From the standpoint of seismic stability, a square itself is stable. However, the Egyptians went further and essentially lowered the centre of gravity of the figure. In short, the pyramid body is a homogeneous stable solid mass. Nothing in it can get broken, there

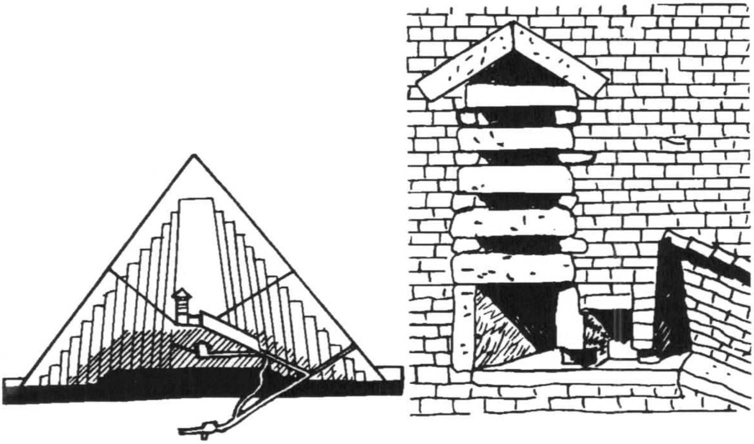

Fig. 22. Ceiling of burial chamber, the Great Pyramid of Cheops

are neither ceilings and domes that can collapse, nor overhanging solid masses that can crash down. Therefore, the earthquake resistance of the Egyptian pyramid is good, and detailed discussion is not needed. Let us go over to Egyptian temples whose constructions are more diverse. The only thing left to be discussed in connection with the pyramids is the burial chamber (Fig. 22), as their principal element. To protect the mummy of pharaoh against probable collapse of the above-laid stones, the chamber ceiling is shaped like a special duplicated unloading system. The purpose of the latter is to unload the structural elements so as to prevent stress concentrations. As you know, overloaded elements are the first to fail during an earthquake. In this unloading system several duplicated horizontal slabs span the chamber room, while the top slabs are leaned against each other. These are most important slabs taking the loads. By inclining the slabs, the bending moment exerted on them is reduced, and they partially work in compression. The Egyptians were well aware of the fact that stone is a brittle material. It well works in compression and poorly in bending at which tensile stresses take place. Two inclined stone slabs form already a simplified vault.

Here some words about the temples. The largest and most magnificent temples were erected in Egypt during the New

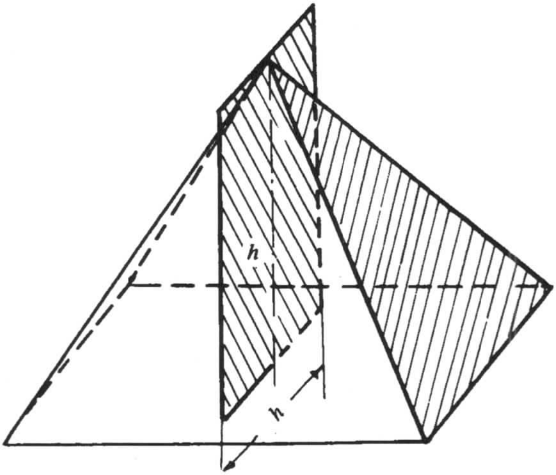

Fig. 23. Geometrical proportions of the Great Pyramid of Cheops

Kingdom times (16th-11th centuries B.C.). We shall not dwell upon each Egyptian temple and its architectural merits. Our task is to discuss the structural techniques used to enhance their seismic stability.

It is good to start with the foundations, or rather with the preparation of the ground bedding under a foundation to which the Egyptians attached great importance, though, to my mind, they had a vague idea about the intricacies of soil mechanics which we cannot yet comprehend. To develop construction techniques, the Egyptians based themselves on the experience gained and excellent intuition. The ground bedding, however, was prepared in accordance with the nature of the site where the temple was to be erected.

If a building was to be made on a plain with soft soil, then this soil was replaced. The Egyptians could be given a patent today to protect that invention, since the method of replacing soft soils was widely used by subsequent generations. After a foundation pit or a trench was dug, the Egyptians took away the soft soil and filled the pit with dry sand to form a required layer. It was actually a part of the foundation, since compacted sand stood to compression very well. At the same time, it was a seismic insulation pillow.

If a temple was to be erected on a rock, the required area was levelled for a future building. Unnecessary rock was removed, and depressions were packed with gravel and sand. The temple of Ramses IV in Der-el-Bakhri was erected on a rock that came to the surface shaped like a slope. To prevent the foundation from possible sliding during an earthquake, the rock was levelled to obtain a horizontal surface. Builders had to cut a 240 by 40 m pit in the rock. The pit bottom was stepped to form 0.5 m high steps. Then this stepped bottom was covered with dry sand to be followed by stone foundation blocks laid on the sand pillow, i.e. a sand pillow was always present between the foundation and the rock. This was the practice of all subsequent ancient builders. Present-day builders neither know nor follow it, unfortunately.

The purpose of sand pillows between the foundation and the ground is twofold. On the one hand, the weight load is uniformly transmitted to the ground, hence equal settlements and the absence of stress concentrations in the foundation. On the other hand, or rather on the same hand, this is already a seismic insulation system damping the earthquake shocks and allowing the structure to slide over the sand relative to the ground that moves during an earthquake. The worst version is when a rigid building is erected directly on the ground rock without damping layers. In this event, nearly all energy resulting from an earthquake shock is conveyed to the building. Light and ductile buildings, say wooden houses, are in a better position, since they can dampen shocks themselves. It is almost beyond doubt that the Egyptians knew well the importance of preparing a ground bedding for a structure. Anyway, as early as the Middle Kingdom times (the end of the 3rd millennium B.C.—the 17th century B.C.), sand pillows, up to 80 cm thick, were made under the column bases. The thickness of a sand pillow depended on the weight of a structure standing on it. In the city of Ramessum the thickness of a pillow under a heavy pylon was twice that under a conventional wall.

The foundations of Egyptian structures feature great diversity. There are imperfect designs when weak lime foundation blocks were put directly on the ground and fairly perfect foundation designs striking us as well thought out. The third pylon of the large temple of Amon has a foundation laid of large stone blocks up to 4 m long and 1 m wide. These blocks were placed in sand edgewise, row after row, with transverse girders between them. This foundation formed a strong core, 38 by 6.3 m in plan and 6 m high. Undoubtedly, the blocks laid edgewise enhanced the strength of the foundation when it worked in bending. We shall speak about it on the pages dedicated to the Greeks.

The foundations under the huge columns named after pharaoh Takhark that stand in the first yard of the large temple of Amon are of interesting design. The foundation pit for the columns is dug in the very dense ground. The foundation itself comprises three courses of free laid stones, each up to 30 cm thick, separated by sand pillows, 10-20 cm thick, with a 1-m thick sand filler under the whole foundation. This laminated foundation is enclosed by a wall of air-dried bricks. As a result, the sand is well preserved, since it is not forced outside the foundation. All these foundations with sand interlayers work as seismic insulators.

The Age of the New Kingdom saw considerable progress in the development of building skill, particularly the creation of strong foundations. Foundations were made deeper, up to 5-6 m, instead of 2-3 m. Conventional limestone was replaced by tough sandstone. The Egyptians obviously tried to make the foundation more monolithic, assembling it of large tightly laid blocks.

The masonry wall was made in three courses with the backfill between the external facings. Thus, in the burial ensemble of pharaoh Joser, which included the step pyramid of Joser dated to the Old Kingdom times, the three-course wall surrounding the ensemble was 15 m thick and 10 m high. It comprised external facing plates of limestone with the gap between these walls filled with fragments of stone and brick. The walls of the temples of the New Kingdom were not as thick as those of more ancient temples, but they were also a three-course type and comprised three independent walls of which the core one was load bearing, while the two external walls were facing. Huge wall blocks up to 10 tons in weight were no longer utilized. At that time builders used small stones with an average weight of several tons. The wall thickness ranged from 1.2 to 4.0 m instead of 15-20 m, as was in the Old Kingdom.

From the standpoint of earthquake-proof construction, the above structure of walls, both in the Old and new Kingdom, featured an essential disadvantage. All the stone blocks were laid in the wall lengthwise one after another with no blocks placed crosswise to tie parts of the three-course wall. As bricklayers could say: "all tiers of stone were flat, and there were no header tiers". The result was that the wall parts were not tied together to make the wall monolithic and ensure its joint work. The wall components could collide and collapse independently. At that time improved wall designs existed already in other countries.

As to the earthquake-resistant construction, three-course walls of more perfect design were used in the Sabaean kingdom that existed at the turn of the 2nd and 1st millennia B.C. on the territory of the present-day Yemen. In that kingdom the walls were laid using the "casemate method". Two parallel walls laid of stone blocks bonded by durable mortar like cement or asphalt were tied by transverse stones header-laid. The void space thus formed was filled with soil, sand, or rubble. The asphalt mortar made facing parts of the wall slightly ductile. The transverse stones ensured ties between these parts and, thus, the wall integrity. The soil or sand inside the wall dampened well its oscillations during an earthquake.

Evidently, the Egyptian builders were aware of structural disadvantages of their walls and took purposeful measures to make the walls ductile, monolithic, and capable to dampen shaking caused by an earthquake. What were these measures?

First of all note that practically no mortar was employed in the Egyptian masonry until the Roman Age. Traces of gypsum were found in few cases, but it is unknown whether it was used as a mortar or as a lubricant in laying stone blocks in place. As was said above, the mortar was not important for such huge stone blocks as those used in Egypt. The stones were held in place by gravity, and to tie them stronger with a view to making the wall monolithic, cramps were utilized; those employed by the Egyptians were called "dovetails" (Fig. 24). Use was made of them as far back as in the construction of pyramids. The relevant recesses were cut in the upper part of two stone blocks to be tied together, and the cramps were fitted into the recesses. Both were shaped like a dove's tail. All stones of the wall were thus locked to one another.

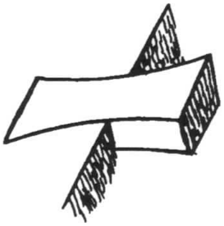

Fig. 24. Dovetail to tie stone blocks

Note that such ties were always arranged along the wall, and never they were arranged to work vertically and crosswise, as the case will be later in Greece. Maybe, the Egyptians specially tried to provide independent work of the three courses of walls. The laminated structures featured increased damping.

The cramps in Egypt were made of wood, granite, copper, or bronze. Archeologists still now find "dovetails" made of African ebony. The stone blocks of the Palace of Knossos we shall speak about later were also tied by wooden cramps.

The temples in Egypt had flat stone roofs supported by columns and girders also made of stone. The girders supported by the columns were also locked to each other by a dovetail joint. The tenon of one girder was fitted into the relevant recess of another girder.

Later, in the 4th millennium B.C., other methods of tying stone blocks to each other were devised. An example is the temple of Isid in Delta in which a facing stone block had a tenon on its back side that was fitted into a hole made in the next block. Other stones in the temple had T-slots used to tie the facing stones to the inner blocks by metallic cramps.

Of interest is the technique of laying stone pylons of temples, an important architectural detail that helped to decorate entrances and gateways of temples. It goes without saying that pylons had stable shape, a wide base, and a narrow top part at the expense of inclined walls. The irregularity of horizontal and vertical seams on the pylon surface was conspicuous. This is because the cut stones comprising the pylons had different shape and dimensions. Some cut stones overlapped others, some had projections that entered adjacent stones. The result was a mutually tied and uniform in strength masonry of the pylon.

I would like to say some more words about the design of flat ceilings of Egyptian temples. As was mentioned, taking into account possible shifts of temple structural elements due to nonuniform settlements or in earthquakes, Egyptian builders provided flexible ties between these elements with the aid of various cramps and projections. A very specific structural design of joints was found between the ceiling girders in the large temple of Amon. The end of one girder had two rounded "beaks" which fitted in assembly into the relevant holes of any other girder forming a chain of interconnected girders. Note that there were two such "beaks" and that only in rare cases the ceiling girders were made of one granite piece. More frequently they were made of two or four flat stones placed one on another. These facts tell us that the Egyptians were good judges of the reliability theory and understood that stand-by elements should be used with such a nonreliable brittle material as stone whose properties had a wide range. However, the Egyptians did not yet know that to increase the resistance of combined girders to bending, their elements should be placed side-by-side, rather than flatwise one on another. The Greeks will hit upon this idea. Since we are interested in the weight of Egyptian structures, I will present some data. In the temple of Amenhotep (Akhematon) III in Luxor some monolithic girders weighed 100 tons and over, while combined girders in the same temple comprised two beams, 20 tons each, placed on each other. In one of the temples of Karnak the weight of combined girders reached 72 tons. To form the roof, placed over the superbulky girders as bulky flat blocks cramped to one another were laid. The thickness of these 3 to 5 m in length rectangular blocks varied from 35 cm to 1.5 m, with the weight ranging from 7 to 90 tons, respectively. Some temples had roofs made of several layers of slabs. Now you understand what an important structural element a column is. Let us discuss columns in more detail.

For all peoples a column was not only a structural element supporting the roof, but also an architectural decoration element. The more so with the Egyptians who used columns as the principal decoration element inside a temple, because columns stood thickly and occupied greater part of the internal space. There were so many columns in temples that they could be compared with a bunch of flowers, the more so that the capitals of columns were frequently shaped like a closed or open flower of lotus. A small temple of Tutmos III had 92 columns in an area of 38 by 28 m, the largest columns being 1.33 m in diameter spaced only at a 2-metre interval. Many of such examples may be given. Certainly, a structure with girders and ceiling slabs so heavy, which were supported by a bunch of thick columns, was extremely heavy.

The first stone columns were used in the architectural ensemble of the pyramid of Joser (28th century B.C.). Those were built-up columns, 5-6 m high, which had up to 30 layers of small-stone masonry without mortar. It is clear that such a column would collapse when affected by an earthquake, unless the horizontal layers were thoroughly fitted to each other. The column structure must provide uniform loading and squeezing of each stone layer, which is very difficult to obtain even utilizing the present-day techniques. Such columns, however, were erected. Later monolithic stone columns were made whose construction continued in the Middle Kingdom times. We shall not consider the advantages of monolithic columns. This is an ideal case from the viewpoint of stone structure resistance to earthquake loads. It would be good to have hinges, ductile at the best, at the ends of such a column. To cut out a whole huge monolithic column, free from defects, of a bulky stone block is a difficult task. Moreover, it is not easy to find such a huge piece of stone. Then in the New Kingdom times use was again made of built-up columns, but of another structure.

Unlike the time of Joser, during which the masonry was laid of small stones, 1500 years later larger column blocks were employed. Each course now consisted only of two half-shafts, 0.5 to 1.0 m high. Depending upon the size and material, the weight of each half-shaft ranged from 6 to 10 tons. To provide uniform loading of these columns for their strength and reliability, the horizontal surfaces of half-shafts ought to be well fitted. This was easier to be done with two surfaces of a joint than when such surfaces were many. To ensure the local stability of built-up column elements, half-shafts were laid so that the positions of vertical joints might be aligned only in every other course. In addition to the immense vertical load holding the column elements from coming loose, the half-shafts were tied at the joint by wooden dovetail cramps fitted into special recesses cut in their upper parts. In the large temple of Amon the cramp was 38 cm long with the width of 11 cm. A small width of wooden cramps tying multiton stone half-shafts suggests that the cramps were no more than assembly elements, but the study of later Greek architectural monuments showed that the cramps were weak, though structural elements. Later on metallic elements were substituted for wooden cramps. I want to call your attention to one detail. The elements of column drums were horizontally tied to one another, while there was no vertical tie between the column drums. This tie was not needed, as they were vertically tied by the immense weight produced by the girders and ceiling, which replaced cement utilized today to bond stones. These built-up columns survived already for more than three thousand years and it is difficult even to imagine the number of earthquakes they endured.

In short, a closed system formed by thickly laid out columns, which were tied at the top level by longitudinal and transverse girders jointed by ductile cramps and ceiling slabs, and divided into limited in length individual sections proved very stable under earthquake conditions. Because the ties between the structure elements were not rigid, while the ground bedding was prepared as homogeneous, the gigantic weight was uniformly distributed. Oddly enough, the failure of one column did not lead to a collapse of the whole system; only the section involved was ruined. The remaining structure kept its balance being held by the immense weight.

We have briefly familiarized ourselves with the construction of enormously heavy buildings in Egypt that survived during 3-4 millennia under fairly high seismic conditions. I don't know about you, but my idea of ancient Egypt is associated with mysterious unknowable wonders. Very likely, this remained from my childhood. This is also the case with earthquake-resistant constructions of ancient temples. During their multimillennium life they underwent lots of earthquakes. Their weight ought to give rise to inconceivable inertia seismic loads, and for sure the temples

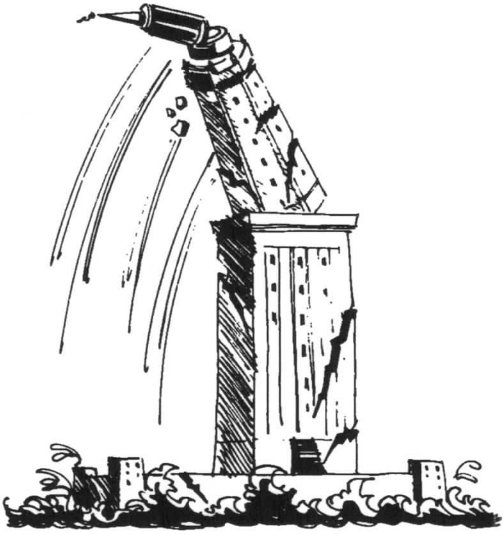

Fig. 25. Imagined collapse of one of the world wonders—Pharos of Alexandria

were to collapse, as they obviously conflicted with one of the major principles of earthquake-proof construction—the requirement to reduce the structure weight. Besides, the temple load-carrying structures were made of a fragile material—stone, while the joint ductility was a controversial question. I attempted already to attribute the seismic stability of these superheavy structures to the interaction between the ductile ground and the heavy building, but this was not enough. To explain the phenomenon of the earthquake resistance of Egyptian temples, their detailed investigation from these standpoints is needed. However, it is absolutely clear that ancient Egyptian architects had their own outlook on how to erect temples resistant to earthquake shocks. I hope, we share views to some extent.

Well, now some words about the 3rd wonder of the world, the Pharos of Alexandria (Fig. 25). By 280 B.C., during the reign of the kind Ptolemy, a gigantic lighthouse was built on the island of Pharos, near the city of Alexandria, under the supervision of the architect Sostrat Knidsky. The purpose of the lighthouse was to make easier the approach to harbors in Alexandria, which was hardly accessible because of Nile silt depositions. The lighthouse was a three-storey tower, about 120 m high. The base dimensions of the lower rectangular part of the tower were 30.5 by 30.5 m. The second storey was an octahedral tower. The third storey was a lantern in the form of a dome supported by eight columns under which the light was located. All this was crowned by a bronze seven-meter statue of Poseidon, the Greek god of the sea.

The whole structure stood on a rock and was built of local limestone slabs and faced with marble. The lower huge part had rooms for the guard, storeroom for the fuel, and spiral stairs by which fuel was delivered by asses to the lantern. Unfortunately, we know nothing about ties between large limestone blocks of which the lower part of the lighthouse was made. They used no mortar, and nobody knows whether there were metallic cramps. However, the limestone of which the tower was built is known to be a fragile material with insufficient strength. Therefore, it is clear that with the given proportions of the structure, its material and rock base, the Pharos of Alexandria was a rigid structure with a small period of natural oscillations. No seismic insulation measures were taken, and the seismic energy of the rock base was conveyed to the structure shaking and destroying it. As early as the 2nd century, the top part of the lighthouse collapsed, and the structure became even more rigid. During the next earthquake in the 4th century, the lighthouse went still lower. The lighthouse turned shorter and more rigid with each earthquake. At the end of the 10th century an earthquake left only 1/4th of the tower. The earthquake of the 14th century finally ruined this glorious architectural masterpiece of the past, which could not adapt itself to earthquake effects [5, 6, 7, 9].

So, we have visited three great river civilizations. If the history really develops spiralwise, then we have already made two turns. The first one covers everything most ancient, i.e. the home of Adam, huts for early man, megalithic structures. The second turn of the history spiral concerns the earliest civilizations that gave rise to further development of human knowledge. Now we start the third turn during which the heights were achieved in arts, human spirit, architecture, and even in the earthquake-proof construction we deal with. This turn of history is represented by Greece, Rome, and Byzantium. This will be followed by the fourth turn represented by the early Middle Ages, from the Caucasus to Japan. I do not know what further "development" can be called, either the fifth turn or the history that goes from a rising spiral to a fall down spin. You are to decide. Now, to the third turn.

Everything About Earthquake Resistance Of Greek Age Structures

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The Minoan-Cretan Culture

Let us start our journey to the architectural monuments of the Aegean world with the city of Troy, because it was the very place where before the 2nd millennium B.C. the culture was at the highest level of development, along with the Cyprus, Lemnos and Lesbos islands. Then the priority was taken by the Crete island, then by Mycenae, and only after this the best monuments of architecture were erected in the mainland Greece. High seismicity of the Aegean sea regions is indicated by numerous islands, hays and zigzag-like shores that formed as a result of earthquake activity taking place in this area. The ancient Greeks and their ancestors were well aware of this formidable element and tried to control it from the past times. Frequent earthquakes in this region are mentioned in numerous remaining stories of interest which tell us, often to the point, how earthquakes influenced events in the country. These stories are so entertaining and at the same time informative that I cannot help retelling them in short.

Referring to Pausanias, we read that during the second year of Olympiad 125 the Celts assaulted the town of Delphi famous not only for its oracle, but also for the custody of treasures. The united forces of the Hellenes took the field and inflicted the first defeat on the barbarians. As the night set in, the Celts encamped and at midnight they heard thudding. Being aware of enemy approach, they snatched at their weapons, took up their formations for battle, and being seized by madness in the dark, rushed at killing each other. But the booming of underground elements known by the Greeks could not plunge them into madness. There was nothing for them to do but capture booty from the enemy in the morning.

Diodor of Sicily tells a story about even more severe earthquake in the same region of Delphi. When the Persian hordes under the command of Xerxes invaded Greece, some troops were directed to seize Delphi and burn the temple of Apollo after capturing the total treasury of Greek states. Of course, an earthquake occurred accompanied by heavy rain, wind, and lightnings. The collapsed rocks killed many invaders and the Persians ran away full of horror and fear.

An earthquake was best used by the inhabitants of the island of Rhodos. According to Polybius, an earthquake destroyed the colossus of Rhodos—the wonder of the world we shall speak of a bit later, most of the walls and wharves. The inhabitants of Rhodos behaved wisely, in a manner it is done today. They directed their envoys to the neighbouring cities and kingdoms where the earthquake was described as so horrible that the neighbours rendered them help far in excess of the damage caused by the earthquake.

There are many of such stories, but we shall return to the legendary Troy situated on the Aegean sea coast and praised by Homer in the Iliad. The archeological excavations carried out by Schliemann and Derpfeld have shown that the Trojan mound contains at least nine cities of Troy. Troy 1 arose two millennia before the Troy described by Homer, at the turn of the 4th and 3rd millennia B.C. The subsequent cities of Troy formed successive cultural layers. The city of Troy seized by the Greeks with the aid of a war ruse of Odysseus was Troy 7. According to a legend, being aware of the Trojans' simplicity, Odysseus proposed to make a wooden horse also called Trojan horse and hide him together with other heroes in it. The other Greeks were to leave the coast after demolishing their camp to demonstrate their departure. He believed that simpletons Trojans would take the horse as a booty to the town, he and warriors would come out from the horse at night and open the gates of Troy. Then the sailed away Greeks would return and slaughter the town. That's the way it happened, and Troy 7 fell.

From the standpoint of earthquake-proof construction, Trojan horse was an ideal aseismic structure that met all the antiearthquake protection principles stated above. Its dimensions were moderate, and the horse housed the Greek warriors with spears and was about 2- or 3-storey building in size. The construction was symmetric and made of wood, a ductile and light material. Besides, it was well insulated from earthquake loads by means of wheels the horse stood on.

The buildings of Troy itself lacked such an ideal resistance to earthquakes, since they were built of other materials and had different dimensions. For our objective we shall consider Troy 6 established by Greek tribes, which prospered by the middle of the 2nd millennium B.C. This wealthy city with good buildings was far larger than the city of Troy 7. Nevertheless, Troy 6 was ruined by a severe earthquake in the 14th century B.C. The earthquake-resistant measures then used were not sufficient. These measures were the following.

Shown by excavations, Troy 6 was a defence system, magnificient at that time, which comprised walls, towers, and auxiliary accommodations built of large stone blocks that were well dressed to fit one another and laid in uniform horizontal tiers. Some blocks weighed 2-3 tons. A part of long stones were placed across the wall, in a "header" manner, to add to the wall strength and monolithic character. The walls, towers and buildings had foundations laid of very large blocks and placed deep on the rock. In case of uneven rock surface, a special bed was cut for the foundation. For stability the walls and towers had a large external rake. All these measures were to improve the earthquake-resistant masonry devised at that time.

By the way, somewhat different structure of earthquake-proof walls was used in the ancient "prehistoric" Troy. To make a wall ductile and monolithic, it was combined of wood, clay, and stone (Fig. 26). This more ancient wall was likely to be more earthquake resistant than the walls built merely of large stone blocks. Look at this ancient wall—everything is thought out in it. The base was done of thoroughly fitted stone blocks laid with joint bonding. Next came a wooden flat framework of beams tied to each other the voids in which were blocked up with air-dried bricks. Above

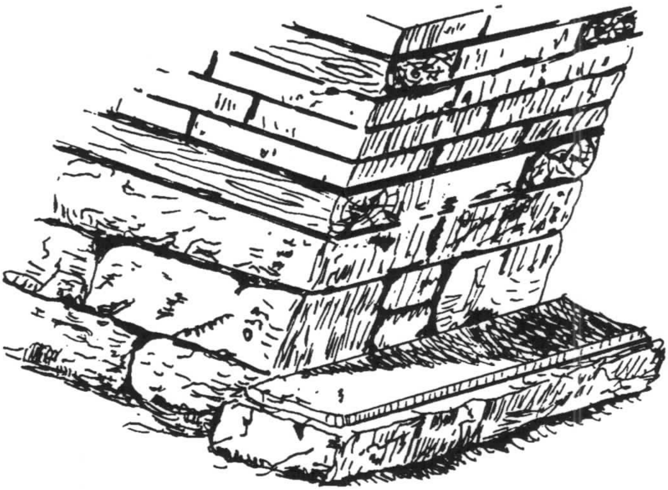


Fig. 26. Walls of ancient Troy combined of stone, wood, clay

it there were three tiers of air-dried bricks and again a wooden framework, and so on. It is clear that such a wall combined of several materials featured the properties of strength, ductility, and monolithic character, and, maybe, of seismic insulation at the expense of reflecting surface seismic waves by the rigid stone interlayer.

After Troy, following the chronological order and our interests, let us consider the Great Palace of Knossos located on the island of Crete and related to the Middle Minoan period of the Aegean civilization (2100-1600 B.C.). Knossos, the city of the legendary king Minos, a famous pirate, was excavated by the English archeologist Sir Arthur Evans and known for the ruins of large ensemble, 24 000 sq meters in area. Much experience in the earthquake-proof construction was gained on Crete known for high seismicity. There even existed a special cult of unquenchable fire dedicated to the God—"Earth Quaker". By this fire the citizens were constantly reminded about the disaster threatening them. The major earthquake-resistant measures used in the palace of Knossos were as follows.

Most popular construction material was gypsum of which large stone blocks were made. From the standpoint of earthquake-resistant construction gypsum was a poor material, too brittle and insufficiently strong. All this was well known to the builders of Knossos palace who tried to impart some ductility and maximum strength to the wall masonry. First of all they thoroughly made the stone blocks fit one another. No mortar was used, the stone blocks being tied by wooden dowels to impart ductility to the masonry. The outer thick walls surrounding the palace were interesting. There were no special defence walls around the palace whose functions could be performed, if necessary, by the outer walls. Besides, structurally, highly stable outer walls provided reliable support to all the internal structures of the palace. The outer walls were of three courses and were faced with edgewise placed plates alternated so that some of them were laid parallel to the wall and some crosswise to provide bonding of the facings. The emptiness formed between the plates was tightly packed with building rubbish. Of greatest interest was the fact that the internal wall masonry was thoroughly reinforced vertically and horizontally with wooden beams (Fig. 27). In exactly the same manner, stone blocks and wooden beams were utilized to tie walls to each other and to ceilings to form a united closed system, making the building antiearthquake. Moreover, much wood present in the stone masonry of the walls cut down their weight.

The wooden columns used in the palace of Knossos were also of interest. The columns were wider at the top and narrower at the foot, and they looked unusual (Fig. 28). However, good thinking shows that this is correct. The ceiling beams were supported by the column top end, while the log butt end formed the column capital suitable for fitting the bearing parts of beams. A hinge was readily formed at the column foot, which made the column work so that it could only be compressed rather than bent.

On Crete much emphasis was laid on the preparation of the ground bedding for the building. To make it uniform, even minute irregularities of the ground bedding were thoroughly levelled by cutting away projections; depressions and crevices were filled with building material. Level grounds in the form of steps were created on the hillsides on which the structures were erected. Formed

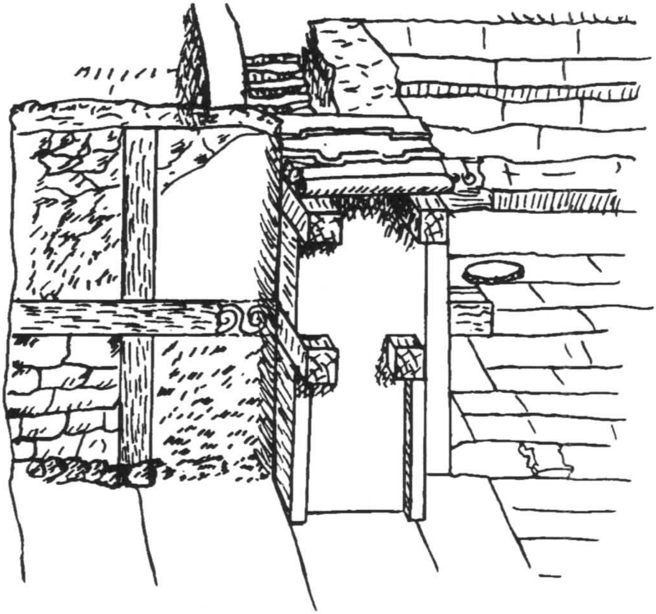


Fig. 27. Wood-reinforced stone masonry in Knossos

between the rock ground bedding and structure foundation without failure was a sand-gravel layer aimed at uniformly distributing the load caused by the foundation, dampening earthquake shocks.

There is one more fact of interest. The buildings of Knossos had at least three storeys. As a rule, the ground floor was built deep in the ground and had small-sized rooms because there were more longitudinal and transverse walls than in the upper storeys. This provided a stronger and more reliable base for the upper storeys. The principle was exactly the same as that in the future Roman structures in which underground substructures that comprised a system of walls and vaults were built on poor grounds to ensure a reliable base.

Many enigmas are associated with Knossos. For example, why were there no defence walls around it? Did the inhabitants of such a wealthy palace have no enemies? Or one more enigma. It follows

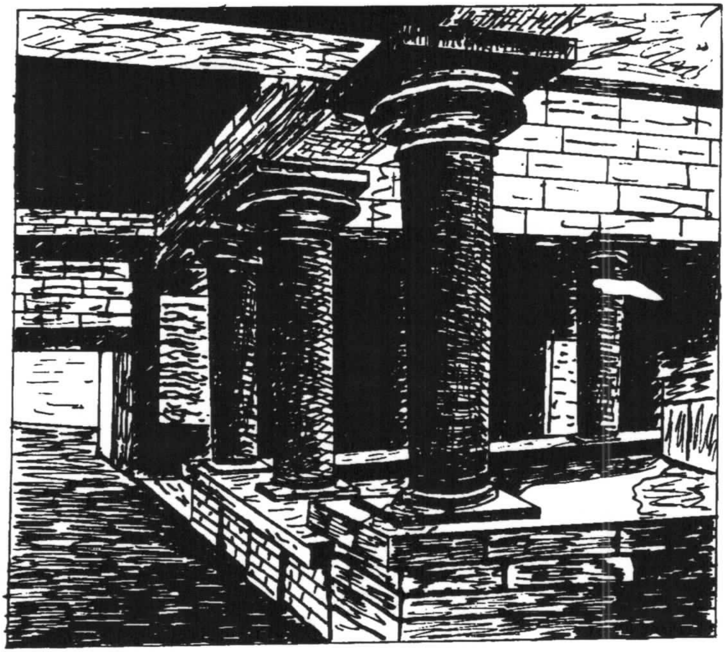


Fig. 28. Wooden column in Knossos that widens with height

from excavations that the bedrooms were, as a rule, located on the ground floors. Why? It was even stated that Cretan citizens took shelter from earthquakes underground. Actually, even at small depths the amplitude of surface waves decreases greatly to lessen earthquake shocks in the underground bedrooms compared to the ground surface. In this event, however, the ceiling above the ground floor ought to be strong enough to withstand loads caused by the collapsed upper storeys. Maybe, they built earthquake shelters on Crete to protect sleeping citizens against earthquakes.

Knossos was situated in the most active seismic zone of Crete and, accordingly, was ruined by earthquakes frequently occurring in this region. Apparently, the aseismic measures that were taken, some of which had been described, were insufficient to allow the palace to survive. This is naturally, since the main flexibility and monolithic character was imparted to the palace by such a short-lived material as wood.

Another very interesting architectural ensemble of that time was represented by Mycenae that were related to the Hellad mainland. The golden age of Mycenae fell on centuries 14-13 B.C. At that time, the Greek mainland was divided into small tribial alliances that were at enmity. The country was restless. As a result, many well fortified settlements were erected one of which was Mycenae. Situated nearby were also well fortified Tiryns, Argos, and others.

The defence works of Mycenae were laid out on the crest of a hill. There were unassailable cliffs on two sides, and only on the other two sides, where the rock was gradually sloping towards the valley, massive inaccessible walls rose.

The walls were made of very large close-fitting irregular stones. Subsequent generations attributed the walls of the citadel built in this fashion to the mythical one-eyed cyclops, hence the name cyclopean masonry. Huge irregular stones were raised with unbelievable difficulties and worked into place. Bonded to one another by irregular shape and gravity, the stone blocks firmly held together, thus forming a strong masonry (Fig. 29). In places of importance, in order to reinforce the masonry still more and prevent stone blocks from sliding loose in case of earthquake shaking, wooden vertical dowels were inserted along the horizontal joints into holes in the upper and lower blocks.

The foundations under the defence walls were made in a highly qualified manner. First of all to prevent the walls from sliding along the slope, a special bed was cut in the rock into which large foundation blocks were placed. These foundation blocks formed a wall base wider than the walls themselves, thus adding to their stability. For the same purpose the walls were given the so-called "egyptian" profile, a wide base gradually narrowing upward.

The city of Mycenae was notable for its remarkable monumental Lion Gate (Fig. 30) that stand more than 30 centuries till our days. The gate is built of four huge stone blocks to form a 3 by 3 m square aperture. One block is used as a threshold. Two other vertically standing blocks support a fourth one that ceils the aperture. This gigantic block is 4.5 m long and weighs 20 tons.

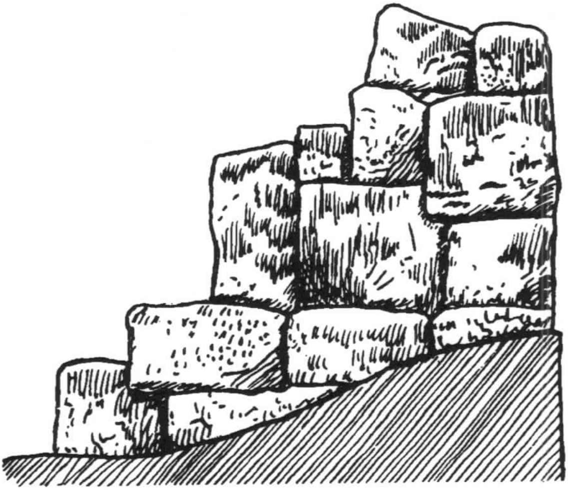


Fig. 29. Cyclopean masonry of ancient Greece, Mycenae

The design of this gate is such that the weight of the above masonry is not transmitted to this fourth stone block, since the above-gate masonry forms the so-called corbel arch built by uniformly advancing the courses from each side until they meet at the midpoint. The formed void above the top block is closed with a triangle stone that depicts furious lions holding a column. Note that the column shape is similar to that in the palace of Knossos, the wider end at the top. In this case we again deal with a corbeled system, as in the pyramid of Cheops. The only difference is that in the latter case they tried to reduce bending moment loads, and in the former case the objective was to completely unload the above-laid tiers of stone. The corbeled system of this type became known as the "unloading triangle", assuming this system to be originally used in the Lion Gate. As we shall see further, in Armenia this triangle will take the shape of a semicircle and will simultaneously replace the top spanning block and a corbeled triangle.

Some more words should be said of the picture found on the corbeled triangle of the Lion Gate. Standing on their hind paws,

Fig. 30. Lion Gate—an example of perfect stone structure

infuriated lions who hold and defend the wooden column symbolize the destination of the Mycenae fortifications, i.e. to defend the residential complex and its inhabitants against enemies. The wooden column widely employed in the residential construction of Mycenae and Tiryns stands in the triangle for dwellings and their inhabitants. The columns of Mycenae are much alike the columns of Knossos, but have distinguishing features. Besides the same flat bearing, stone square plates at the top and foot, the top wide end of the column is furnished with a metallic clamping ring protecting the column from cracking.

The construction of this gate fills you with admiration of how much ancient people knew about the work of a material in a structure. They obviously were well aware that the stone perfectly stood to compression but could not withstand tensile loads. That is why they provided a corbeled triangle above the girder under bending load in which the stone in the lower zone was subjected to tensile stresses. Besides, since the bending moment of a stone is at its maximum at the centre of the girder, its central portion was made thickened. To add still more to the unloading of the

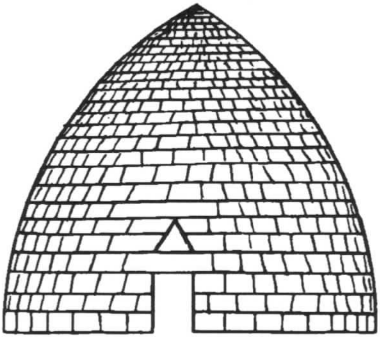


Fig. 31. Antiearthquake arrow-shaped dome of the tomb of Atreus

central portion of the girder and to lock the top stone block in position, builders weighted down its ends by the stone masonry of the false vault base and thus made the central portion statically indefinite, as if to withdraw some amount of bending moment from the span centre towards the girder ends. While analysing the design of this gate, it comes to mind that such a cyclopean stone construction could not be better designed even by the modern engineer using most advanced theory of structure design.

There are other structures of interest in Mycenae. Survived in the "Lower town" are most remarkable great tholos tombs that are peculiar in design. These structures feature simplicity and shape harmony, accurate workmanship, and, as a result, high resistance to earthquake effects. By way of example, let us talk about the tomb of Atreus (the 14th century B.C.), the legendary ruler of Mycenae, which is known as the "treasury of Atreus". The design of this tomb was brought to perfection. Many older tombs collapsed long ago due to some blunders, while the tomb of Atreus, owing to its perfect structural design, has already stood, true underground, almost 35 centuries, showing high resistance to earthquakes.

The principal part of the tomb, the burial chamber, is 13.2 m high, and its circular outline in plan is 14.5 m in diameter (Fig. 31). The dome curvature starts at the floor and is formed by the uniformly advanced stone block courses towards the center point with subsequent chiselling and dressing along the curvature after the blocks have been laid. The largest blocks are placed in the lower portion of the wall; the blocks become smaller and the walls thinner with tomb height. The figure demonstrates the lancet-shaped profile of a dome. Though it was mentioned before, I cannot help repeating that such a dome configuration agrees well with the earthquake-resistance requirements. The dome masonry is continuous, except for two door apertures, high and low. Both are spanned by stone girders above which, according to the false dome system, triangle corbeled openings are made similar to those of the Lion Gate. In fact, the entire dome of the tomb of Atreus has been laid in the corbel dome manner, i.e. by projecting all blocks of each masonry tier progressively towards the centre with the tomb height. Let us dwell upon some details of the design. The material for the tomb construction was local siliceous limestone of high density and strength. Certainly, no mortar was used in this case. The stone blocks were laid thoroughly fitted in a dry run to provide, on the one hand, high strength of the structure and a high damping coefficient, and, on the other, possible ductility at significant loading levels. At the points of importance, near the door apertures, the blocks were tied to each other by cramps of the dovetail type, which is characteristic of the Greek world. More than that, the dome curved outline started directly with the foundation, therefore, the dome-caused thrust was transmitted to the foundation and ground base. But it must be borne in mind that the tomb was situated underground and all its tier rings were compressed by the soil fill. Evidently, this not only reduced the dome thrust, but even provided outside compression of the dome. In addition, note that underground structures are frequently under more favourable conditions than surface structures, inasmuch as the earthquake effects abruptly diminish with depth. I think there will be an opportunity to consider this problem in more detail.

As follows from the above-said, the construction of the tomb of Atreus meets the major principles of the earthquake-proof construction: good proportions, axial symmetry, lancet-shaped dome, lightening with height due to reduction of the dome thickness, elimination of stress concentrations at the openings provided in the dome, strong material, underground location, outside compression by the elastic-ductile ground medium, possible sliding between stone blocks. These aseismic measures were sufficient to allow the tomb of Atreus to exist for 35 centuries.

Similar, but more complicated construction of an underground mausoleum, whose idea is also perfect, we shall observe in the Regal tumulus when we reach the Bosporus kingdom. It is interesting whether builders of the latter mausoleum knew anything about the former mausoleum.

The study of ancient structures shows, much to our astonishment, that builders of the past took care to solve too delicate a problem of eliminating stress concentrations in a structure. There are two examples to prove it. An ingenious unloading system is found above a wide door aperture in the domical tomb in Menidi. As a result, the girders spanning the door aperture carry no overload, except their own weight. The design of the system is as follows. Heavy monolithic girders are placed above the door aperture in a thick wall, and four tiers of thin plates are laid above them with narrow clearances between the plates (Fig. 32). One can see that there is neither overload exerted on the girders nor stress concentrations.

Another example concerns the above-mentioned fortified citadel of Tiryns, located not far from Mycenae and built somewhat later, the unassailable acropolis of which with the walls and a new palace was completed in the 14th-13th century B.C. More impressive than the palace are the defensive works of Tiryns with heavy solid walls of cyclopean masonry, from 8 to 17 m thick. It comes as a surprise why these structures were not ranked among the wonders of the world. Revealed are the secrets of constructing Greek temples and even Egyptian pyramids and temples that were built of multiton stone blocks of regular, most often rectangular shape. But nobody has yet fancied the techniques of laying the cyclopean masonry of the type used in the Tiryns' fortifications when multiton stones of irregular shape were worked into place. Of the entire diversity of the fortification features of Tiryns, I call your attention to only one structural subtlety used. The locality in which the defensive walls of Tiryns were built is very irregular for which reason the walls themselves have a zig-zag longitudinal

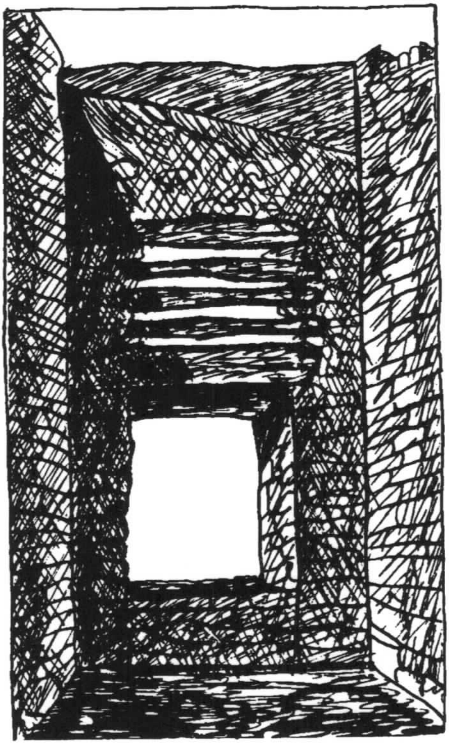


Fig. 32. Relieving system above entrance to the tomb, Menidi

profile. The walls now come down along a hill slope, now turn to the nearest rock, now abruptly turn to satisfy the defensive requirements. The result is that there are no straight walls even of short length. From the viewpoint of earthquake resistance, this is favourable, on the one hand, since walls at an angle to each other perform the functions of counterforts, but, on the other, walls at different angles with regard to the seat of earthquake will be shaken in a different way. Moreover, wall settlements differ with hill slopes. If this non-uniform wall were made continuous, stress concentrations and associated cracks would occur in it during an earthquake. This was well understood by architects of the past, and they invented sliding aseismic seams. The towers supporting the walls were not at the same time tied to the walls by common masonry, being as if annexes. Thus, a tower collapse did not affect the wall and brought no harm to the defence. Sliding seams were also used between the wall sections and the walls and structures of the palace. The problems of eliminating stress concentrations in buildings were tackled by ancient builders at the present-day level.

Completing a short excursion to the ancient "aegean" architecture, I want to emphasize the following. Comparing the aseismic measures taken here and in later Greek architecture associated with it to the above-considered brick civilizations of India and Mesopotamia, the following can be noted. In the Harappa and Mesopotamia the aseismic techniques were worked out mainly on the basis of intuition and experience gained. They included the bonding of brick work, thickening of wall foot, counterforts, ductile mortars, wood and stone reinforcing. In the Greek world there were a system and knowledge of the fundamentals of structure work that allowed special structural methods to be applied in erecting earthquake-resistant structures. It is well seen and this will be shown later that although the basic building material was stone, a rigid and brittle material, builders wanted to impart the properties of ductility and elasticity to stone buildings and to unite all load-carrying structures into an integral system associated in all directions [5, 7, 11, 12].

Let our acquaintance with the origins of aseismic methods of Greek architecture be completed and, without a moment's delay, we shall go over to the famous Greeks of antique times.

Mainland Greece

The influence of great Greek culture spread, in addition to the mainland Greece, i.e. the southern part of Balkan peninsula, to the cities and colonies of Hellenic tribes that were scattered about the Mediterranean sea coasts, and also to northern area of the Black sea coastal area and Asia Minor. In the 5th century B.C. in the course of victorious Greek wars against the Persians and after the victory over the city of Carthage, the Greeks moved still further deep into Asia and Africa. In the 4th century B.C. the troops of Alexander the Great had annexed Persia, Egypt, reached India and Central Asia, having established a number of Greek-Eastern monarchies. It is clear that given such wide spread of influence with annexing highly-developed countries, mutual exchanges took place in the field of culture and construction skill. There is a point of interest in the history of Greek construction technology. They did not perceive two important things in the construction work that were employed by the East. In their monumental architecture the Greeks neither used domes and vaults, nor the masonry bonding mortar. What was the reason?

It was not a mere chance that neither domes nor mortars were utilized in ancient Greece. Greek builders had their own theory of structures that included their own theory of earthquake-proof construction they followed, utilizing or rejecting one or another construction technique existing at that time. Let us attempt to fancy the notion followed by ancient builders of Greece when they erected temples taking into account the earthquake danger.

Even a brief survey of Greek temple structures leads to a conclusion that a very simple girder-pillar system was utilized with ductile ties between the elements. The vertical load-carrying elements were represented by walls and columns that supported the girders carrying the floor decking. The ties between the load-carrying elements were accomplished with the aid of iron dowels and cramps sealed with lead. All these elements will be considered in structural details later. The girder-pillar system prevailed in Greek architecture both during the classical (5th-4th centuries B.C.) and archaic (8th-5th centuries B.C.) periods.

Since columns and walls of the girder-pillar structure of Greek temples worked merely in compression, while girders in bending, there were no domes and vaults whose thrust would cause additional horizontal loads on the columns and walls, in addition to their vertical compression. Besides, at that time it was impossible to provide a ductile tie between a dome and the walls supporting it. And, finally, to replace the ductile ties accomplished with the aid of dowels and cramps sealed with lead by firm ties using some, say, lime mortar was not permissible. All this would conflict with the girder-pillar system with ductile element-to-element ties, which was used by Greek builders. That is why, to my mind, ancient Greece saw neither domes nor mortars, although they were aware of them and employed them from time to time. Arches laid of wedge-shaped stones were encountered in the burial chambers of burial vaults in the classic period. As early as the 5th century B.C., many vaults of fortress gates were semicircular in shape.

There is one more supposition why the ancient Greeks did not use domes and arches. To take up the thrust of a dome ceiling, additional inactive masses would be required that would add too much to the structure weight. The walls and columns that were utilized could not perform this function. If used, domes would make Greek structures still heavier, and they would be deprived of distinct architectural composition. This would conflict with one of the basic principles of resistance to earthquake, i.e. the antiweight principle.

The fact that builders of ancient Greece tried to make the structure of their unique temples sufficiently ductile is confirmed by the construction of foundations. In classical and archaic periods foundations were built independently under walls and separate columns. Accordingly, unequal settlements of the foundations caused additional stresses neither in the flexibly tied floor and ceiling elements, load-carrying walls and columns, nor in the foundations.

The connection of elements of Greek temples, which is also important, will now be presented.

To secure stones of one tier, metallic cramps were utilized shaped as simple strips, double-T, П-like, and dovetails (Fig. 33,*b*). To tie together the cut stones of two adjacent tiers, use was made of pins, the holes for which being made in the lower and upper stones. In the late Greek structures the shape of these fasteners was improved. Thus, for better attachment to a stone, the pins already had thickenings at the ends (Fig. 33,*a*). Prior to placing the upper stone, the pins were fitted in their holes and sealed in by lead. Then the stone was put in place so that the lower pin end fitted the hole in the lower stone. As the next step, it was also sealed in with lead poured through a special hole. The cramps tying the stones of a tier were similarly secured in place by filling

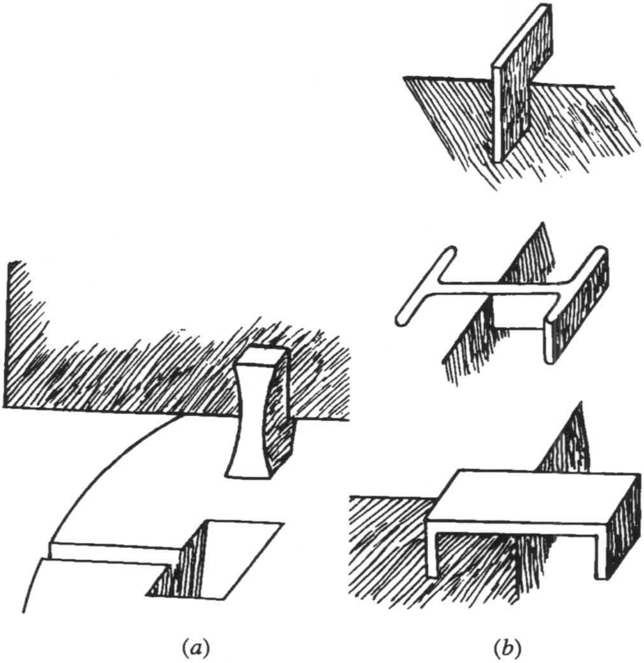


Fig. 33. Tying stone blocks in Greece:
(*a*) pins to tie stones of adjacent tiers;
(*b*) metallic cramps to tie stones in a tier

the holes with melted lead. In the temple of Athenian Parthenon (to be discussed later) wooden plugs were driven directly into marble at the centre of the column shaft. To prevent the plugs from swelling, they were made of resinous wood absorbing little moisture. Wet plugs were driven, which dried gradually with time. Only wood fasteners were used by the Sicilian Greeks in the 6th century B.C. Iron cramps found their application only in the 5th century B.C. There existed combined fasteners, when a metallic dowel was driven into a wooden plug. But fasteners made of pure metal were not encountered unless they were embedded in lead or wood, and it was done not without purpose. Soft spacers of lead or wood cushioned shocks between the hard metal and the hole side in marble during earthquakes, therefore, there were almost no chipped edges of the holes containing metallic cramps shock-protected by lead or wood, i.e. elastoplastic ties were formed to protect the structural elements from direct impacts. These lead-sealed cramps and pins were important elements for ensuring seismic stability of Greek temples. Besides, at the same time the lead protected metallic cramps and pins against rust.

It follows from the above that owing to structural techniques mentioned a Greek temple may not be considered as an absolutely rigid body. It consists of separate stone elements having elastoplastic ties between them and has a high coefficient of damping due to the accurate fitting of stone blocks to each other. Even a column that comprises separate shaft drums with ductile ties is a flexible pillar. Therefore, the Greek temple meets almost all principles of resistance to earthquake effects: good foundations, almost constant symmetry of mass and rigidity distribution, possibility of movement, and a high coefficient of damping due to ductile ties between the elements. Nevertheless, most of Greek temples were ruined by earthquakes, though it would seem that such structures as Greek temples must never collapse because they were free from side thrust, their stone elements were not heavily loaded compared to the stone ultimate strength, and construction ties were elastoplastic and structural elements symmetrically laid-out. However, the point is that the great weight of a stone-beam ceiling, which was raised highly, raised the structure's centre of gravity respectively. Huge masses of material concentrated at a great height caused irresistible inertia seismic forces during earthquakes that ruined the structures. There were no inconceivable, enormous weights characteristic of Egyptian temples, which accounted for mysterious seismic stability of the latter. Greek temples were simply heavy, and their great weights often led to fatal results.

Let us have some more talk before proceeding to antiearthquake measures taken in specific Greek temples. Somebody, may be many of you, may have not agreed with my words that ancient architects distinguished between a structure not resistant to earthquake effects and an essentially different building that well stands to earthquakes. In a seismically stable building everything, from the foundations to door jambs and hydraulic insulation of the roof, must be permeated with the idea of resistance to earthquake effects.

We also encounter this versatile concept of resistance to earthquakes in Greek temples. What is the reason a construction method is used for? Is it for seismic stability, or for some other reason? One is surprised at the skill of ancient builders to solve several problems at once by one structural method. Here is a simple example. Several order systems are known to exist in ancient Greece. An order in architecture is a style, according to which the structural elements must be laid-out allowing for the form and proportions strictly specified for them by a given order. The most popular in Greece were the two orders. The more early Doric order was known for simple and heavy constructions. In proportions the columns of this order were compared to the male figure. Later on the Ionic order was developed. This order of Greek architecture was more light and fanciful with slender and lighter columns resembling a female figure.

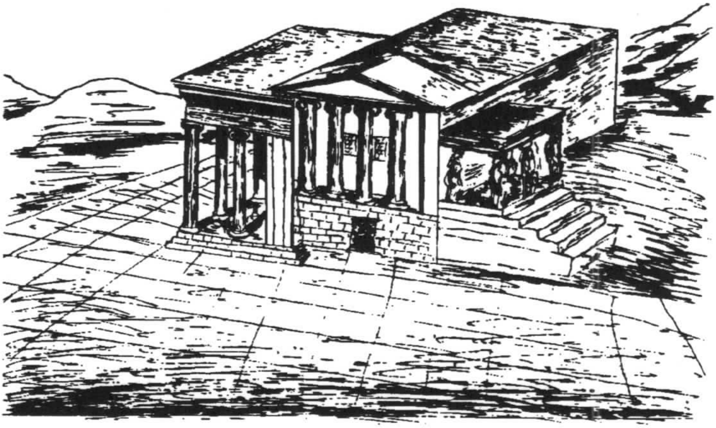
Here is a question for quick thinking persons. What was the purpose of the Ionic order? Was it used for architectural aesthetics and beauty, or may be the objective was to obey our principles of earthquake-proof construction by reducing the weight of the structure? And may be the scroll-like ornaments at the top of the columns not only resemble woman's curls, but also provide more reliable support for ceiling beams.

There is one more example. Looking at the exterior face of a Greek temple surrounded by columns, one sees all columns equal in diameter, standing vertically at equal spans, but this is not so. This regularity of perception is due to correction of optical distortion. To this end, the outer columns are made thicker than the middle ones, the span between the outer columns is decreased, and, finally, they are all inclined inward.

What is it? Was it done to correct the optical distortion, or was it an antiearthquake measure? From the standpoint of seismicity it is obviously correct, since in case of an earthquake the loads at the corner columns will be greater, and these columns must be thicker. The same is with the corner girders whose spans must be reduced, since their loads are greater. Finally, the corner columns inclined inward add to the general stability of the building. Even these two small examples demonstrate that ancient builders could comprehensively solve problems of architecture and construction. The examples combine aesthetics, earthquake resistance, and all other aspects about which we may have no guess. Now the time is to deal with specific structures.

Let us consider the construction of several Greek temples. These are buildings devoted to the worship, or treated as a dwelling-place of a god or gods. They are usually decorated with columns. A temple usually houses a statue or symbol of the God (Goddess) it is devoted to, and inside and outside the temple rites are conducted in honour of a given deity. Naturally, the ancient Greeks put a lot of talant and skill into the erection of these edifices. We shall not follow the chronology in considering some of these temples, rather we shall select what we are interested in, following our logic guideline.

We shall start with dual temple Erechtheion now in ruins, which was built on the acropolis in Athens with shrines to Athene and Poseidon, the earth quaker. Finally, the temple was destroyed in 1852 by an earthquake. However, it was thoroughly restored at the beginning of our age. This temple differs from all other Greek temples by its complete asymmetry. It consists of a rectangular building (Fig. 34) and three porches connected to it that differ in rigidity and depth of foundations. The ground under this edifice is heterogeneous, and the building is situated near a precipice to make the wave picture of earthquake effects complicated. Besides, it is partially supported by the ancient temple of Hekatompedon destroyed during the Persian wars. In this event, we may speak neither of symmetry, nor equal distribution of rigidity and mass. Why did it happen? I refuse to assume that ancient builders who started the design and construction of Erechtheion as late as 421 B.C. were not aware of the symmetry requirements for unique public buildings. It appears that such a complicated asymmetric temple had to be erected to satisfy the intricate design requirements in the given site. Erechtheion was to include the shrine of Athene which contained a wooden statue of Athene known as the most ancient sacred thing on the acropolis that had fallen from the heavens, according to a legend; the shrine of Poseidon—the god of earthquakes and water—with the salt spring where his trident



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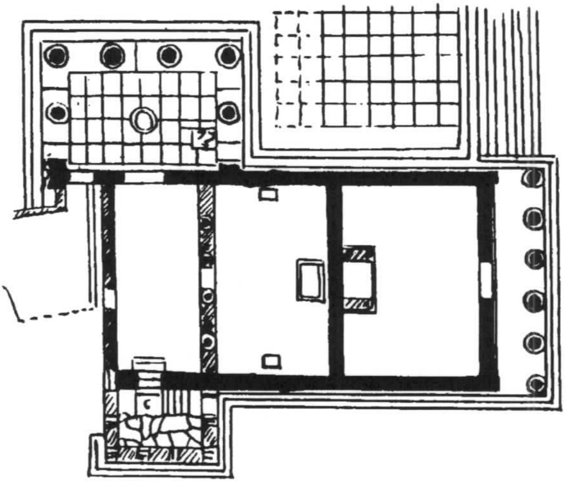


(*b*)

Fig. 34. Asymmetric Erechtheion:
(*a*) general view;
(*b*) plan

struck the ground, the regime of which was not allowed to be disturbed; the shrine of olive, the tree sacred to Athene which she planted for her town; the cage of golden sacred serpent and the tomb of Kekrops—"ancient man", and something more as important.

All that had to be coupled in an architectural way, and since all the shrines were located at different ritual levels of the rock, builders had to construct a temple strange in arrangement. To the point, there is a hypothesis saying that this temple is unfinished, otherwise it would even be more complicated.

Therefore, the builders of Erechtheion were compelled by exceptional circumstances to violate the major principles of earthquake-proof construction: the principles of symmetry and uniform distribution of masses and rigidity. Other structural methods that were known at that time and aimed at ensuring seismic stability of the temple were utilized by them. Moreover, they even attempted to compensate for the unwilling asymmetry. What has been done is the following.

Note, first of all, that during the construction work on the plateau of the acropolis in Athens, the builders had to take into account the rock of Athens. Parthenon, Propylaea, and, of course, Erechtheion are insulated from a direct contact with the rock by means of filled packed soil to provide a uniform ground base for the buildings. The stone foundation of Erechtheion is not a solid massif, because there are individual foundations under the walls and columns. The foundations under the eastern and southern porches are highest and largest, as the rock under them abruptly lowers, which is fraught with the danger of landslide. The main antiearthquake measure in Erechtheion is represented by the dry laid masonry of stone blocks thoroughly fitted to one another with bonded joints and tied by T-shaped cramps and pins lead sealed in place (Fig. 35). To prevent sliding during an earthquake, horizontal surfaces of the stone blocks are made rough with a smooth surface border along the edges to provide accurate fitting of the blocks. The vertical surfaces are finished in the same manner, and this imparts the masonry a high coefficient of friction.

The block slabs of the three-step stereobate upon which the walls and columns are erected and of the plinths are laid flat on

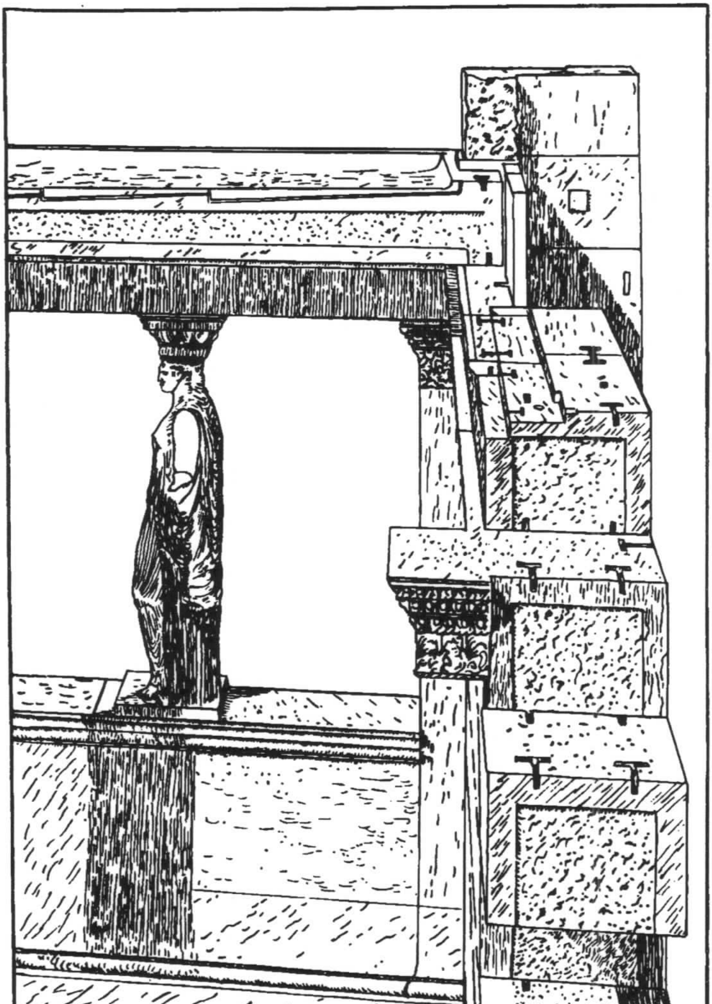


Fig. 35. Example of tying stone blocks in portico of caryatides

each other to form the base binding of the temple closed in the outline. The wall base is made of large blocks up to 1 m high, 1.3 m long, and 0.65 m thick. Above this elongated marble blocks are laid in the wall. These blocks form a course and are interconnected by cramps and pins as shown in Fig. 35.

The planning of Erechtheion takes into account the fact that its western part is heavier than the eastern part (Fig. 34), and the porch of caryatides and the northern porch added to the western part on two sides serve as counterforts to fix this heavy portion of the temple in case of an earthquake. By the way, some investigators believe that the quality of the western wall is lower than that of the other walls of Erechtheion.

Erechtheion has been considered herein to show its complete, antique, as it may be called, asymmetry that is implemented in the design of the given temple. Even the northern and southern porches (caryatides) added to the main building, which, in addition to the aesthetic and worship purposes, perform the function of counterforts, are not symmetrical. This, naturally, caused additional torque moments in the temple's structure during an earthquake. To my mind, this example will help contemporary builders understand that asymmetric buildings must not be erected in highly-seismic regions, inasmuch as high-quality Erechtheion is a unique edifice, and they are unlikely to succeed in building another one. We shall not discuss the construction of Erechtheion ceiling. It is similar to that of other Greek temples, a wood-stone type. The ceiling typical of Greek temples will be considered on another example.

Telling the story of Greek temples, it stands well to reason to consider Parthenon—one of the most perfect masterpieces of architectural art in the world. The temples and public edifices built on the Athene rock in ancient times were ruined by the Persians in 480-479 B.C. After their banishment, at the time of legendary Pericles who headed the Athene slave-owning democracy during its flourishing, restoration of the acropolis started. The widely planned reconstruction was controlled by Phidias himself, the great sculptor and architect of that time. The most important monuments of the ensemble of acropolis were: Parthenon—the temple of Athene (the maiden) built in 447-432 B.C.; the

Propylaea—a ceremonial gate erected in 437-432 B.C.; the gigantic statue of Athene Fighter, and, finally, Erechtheion which was already discussed. Of all these specific edifices, we shall consider Parthenon.

A.S. Bashkirov describes the workmanship of this temple as follows: "The workmanship of Parthenon is remarkable for wonderful thoroughness and splendid clarity in details, each separate block being finished with amazing accuracy. Whatever its place, each block of the masonry tells that its superfinish is not only for its refinement, but also for severe necessity to contribute to the structural stability of the edifice. ... The equal and neat distribution of masses in the temple together with slender verticals imparts the building lightness and highly credible stability". Here are some words about Prof. Bashkirov who contributed much to the history of the earthquake-resistant construction and whose works must be acknowledged in this book. His papers on archaeology of the northern Black sea coastal region were published as far back as before 1917. To my mind, his principal work is represented by the four-volume *Aseismicity of Ancient Architecture* (Antiseismizm drevnei arkhitektury), 1945-1948, Proceedings of the Pedagogical Institute of Moscow, Kalinin and Yaroslavl (up to 300 copies). Today his books are bibliographical rarity whose author is known only to a few people, though the books are unique in contents and interesting in design. Besides, it is known that he started a similar fundamental book on the earthquake-resistant construction of the Middle Ages, but what happened to his manuscript is unknown. The information about Prof. Bashkirov got lost in the city of Yaroslavl, 1948. There is a legend that he predicted a severe earthquake in Central Asia that, unfortunately for him, happened in 1948 in the city of Ashkhabad. Prof. Bashkirov was considered to blame for something unknown to us; a charge was brought against him after which he disappeared. Very few people know his noteworthy works. However, let us return to our Greeks.

As you know, Greek builders paid much attention to the preparation of a ground base. Before the buildings on the acropolis were destroyed by the Persians in 480 B.C., the preparatory work was started for the construction of "Great Temple".

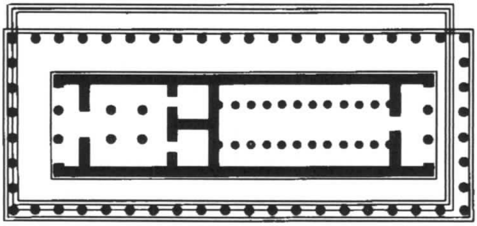


Fig. 36. Parthenon plan

The ground bedding under the foundation of this temple was made in a heavy tightly-compacted fill to where the so-called "Persian rubbish" was added later, i.e. the debris of buildings destroyed by the Persians. A gigantic supporting wall held the fill to form a territory far wider than it was required for the temple. The foundation of the Great Temple was laid by builders in this fill. The progress of the construction was slow, and at the time of Pericles the temple was replanned to start the construction of Parthenon in other proportions, far better from our viewpoint. New builders reduced the length of Parthenon compared to the old temple, but made it wider. They partially utilized the old foundation that became stronger by reasonably shifting the building farther from the edge of the rock. The remaining unloaded part of the old foundation at the supporting wall side served as if a counterfort for the base of the new building. The builders did not take the risk of erecting Parthenon even partially on the rock, as we would do, since the result would be a nonuniform ground bedding. Neither did they use the narrow rib of the rock running from the West to East parallel to the long side of the temple. Placing the building on this rib would threaten to break the temple into parts during an earthquake. The position of Parthenon was determined by these very conditions for the state of the ground bedding, and the requirements for the harmony with the landscape and the eminence of the temple.

Figure 36 shows the plan of Parthenon which is a peripter (a temple surrounded by a single row of columns) with 8 by 17 columns and base dimensions of 31 by 69.5 m. The outside colonnade surrounds the walls of the cella, the sanctuary of the temple, 21.7 by 59.0 m in plan. The columns are 10.43 m high, 1.905 m in diameter at the base; the diameter of the corner columns is 1.948 m. The temple dimensions are given in detail to lay emphasis on the proportional ratios between the width, height and length.

Referring to the plan of Parthenon, there are also internal columns and transverse walls to provide equal distribution of mass and rigidity. That is, the planning of the building meets the construction requirements.

The existing damage to Parthenon tells us that the temple underwent many earthquakes and would survive, if it had not been destroyed by the explosion in 1687 caused by a cannon bomb that hit the powder depot arranged in the temple by the Turks. The explosion blew up the builder's center and scattered the columns of longitudinal facades. Lying in ruins, Parthenon allows us to study in detail the small structural methods used by the ancient Greek builders to protect their buildings against the earthquake effects.

Parthenon was mainly built of marble, bronze in the form of dowels and pins, and lead to seal them up. The properties of these materials were used to create structures resistant to earthquakes. To prevent free sliding of one stone part over another, the following steps were taken: first, their beds were made highly rough, even column shaft drums showed sharp, man-made roughness; second, none of the masonry blocks in the foundation, walls, ceiling girders, even the door casing blocks was laid without pins and dowels performing the function of a mortar; besides, they provided ductile ties between the elements of the structure.

Now let the design of the columns of Greek temples we are interested in be considered. At more ancient times, the columns were cut of large pieces of material and made one-piece. Later, for simplicity of making, and may be from the standpoint of resistance to earthquake effects, the columns were made built-up of individual shaft drums tied by the friction force and central dowels. Since, the built-up column was more flexible than a monolithic one, it could serve as a seismic insulator for the bulky ceiling. The columns, however, could not perform the function of pure seismic insulators in the edifice, since the girders at the top

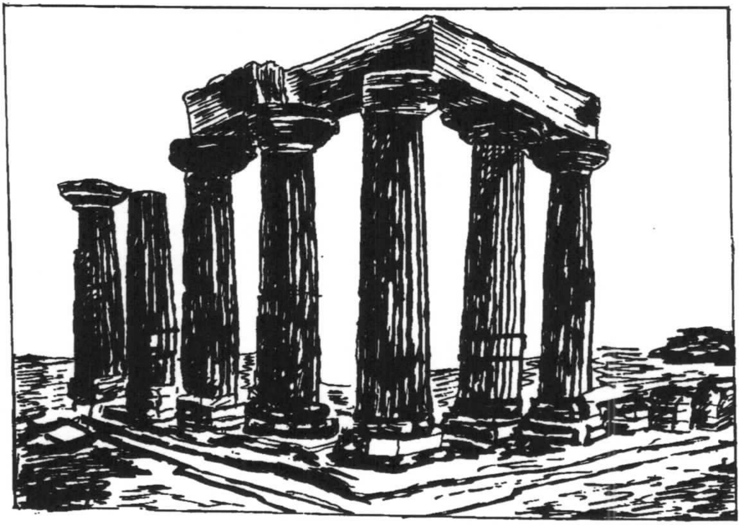


Fig. 37. Temple remains formed the earthquake-insulated system

level connected the columns into a single whole with the more firm walls. As a result, the heavy horizontal earthquake loads exerted due to the great weight of the ceiling were almost completely conveyed to more rigid walls of the cella destroying them first of all; because of their flexibility, the built-up columns were affected by these horizontal loads only partially. After the failure of the cella's walls and collapse of the ceiling parts they supported, the flexible columns survived supporting bulky blocks. In this case the systems of columns worked as seismic insulators. This was proved by the survived fragments seen among the ruins of Greek temples which usually comprise a group of columns with massive architraves lying on them. Such fragments are scattered far and wide where the tools of Greek builders sounded; in mainland Greece, on Sicily, in Asia Minor, and in Iran. An example is shown in Fig. 37 depicting the ruins of the temple of Poseidon, the 5th century B.C., showing white at a height of 60 m, on the cape of Sunion opening the exit to the Aegean sea. The columns of Parthenon were also built up of individual shaft drums which were tied to each other by means of specific rough surfaces made for the purpose and bronze rectangular dowels secured in the centre of the drum. All the columns of Parthenon survived after the explosion carry architraves tying them into individual groups. These separate groups consisting of foundations, flexible columns, and bulky ceiling girders are, in fact, systems of seismic insulation.

Now some words should be said about stone girders working in bending.

Being on guard against failure of the stone load-carrying girders laid on the outside columns, Greek architects of Parthenon minimized the column-to-column span to 2.47-2.51 m. To make the girder laying easier and add to the reliability of these girders, the girders were assembled of three plates placed edgewise. In this case, a failure of one did not lead to a complete failure of the whole load-carrying structure. To the point, note that in more ancient temples the girders were assembled of a few plates placed flat on each other to affect their strength. Later they got a good understanding of it, and the plates were laid edgewise, as the case was in Parthenon. Of course, the Greeks were well aware of how to study the construction experience and use it in their work. Knowing how to dress a stone and also well understanding its strength and deformation properties, the Greeks allowed even for such a "trifle" as probable collision of the girder plates during an earthquake. Brittle stone plates might crack. In order to prevent this, a clearance was provided between the plates when they were placed edgewise. Now some words about the design of Parthenon's roof. The design and elements of the Doric order do not form a problem we are to examine in detail. There are actually two points of importance for us. Marble and wooden elements of the ceiling were thoroughly fitted to each other and interconnected by various stone detainers and also by metallic parts sealed with lead—this is first. Second, we must note that the temple roof with all its components such as beams-architraves, metopes, triglyphs, friezes, wooden rafters with roof sheathing and marble tiles laid on them was very heavy. From the standpoint of our earthquake-resistance principles, the former factor is positive, the latter–negative. At any rate, the ancient Greeks did their best to use those construction techniques that improved the earthquake resistance of their edifices. An example is as follows: there were thin columns within the cella of Parthenon, which were almost as high as the external columns. To reduce the free length of the former columns, being afraid that the long and thin columns would be unstable, the builders made these columns two-levelled by connecting them with beams at a height slightly above the midpoint of the total height. This made them stable. Generally, all these structural methods were aimed at improving the earthquake resistance of Greek edifices. But frequently they were useless compared with the negative influence on the earthquake resistance of the edifices caused by huge weights concentrated at the ceiling level. It was the enormous weight that accounted for the failure of Greek temples. Judging from the damage to its individual parts, Parthenon came through many earthquakes. Only earthquakes could shake it so as to cause multiple collisions of stone blocks with resultant chipping along vertical joints of the elements. Cracks in the floor slabs also point to the earthquake waves.

Many Greek temples are known to be destroyed by earthquakes. In what condition Parthenon—the ideal implementation of the Greek construction skill—would be today is difficult to say, since, as you know, it was destroyed by the explosion of a Turkish powder depot that was quartered there. To sum up all that has been said about the ancient Greek temples and their resistance to earthquake effects, a conclusion can be made from the viewpoint of our earthquake-resistance principles that these temples had two disadvantages, i.e. highly located great weights and nonuniform rigidity of the structure manifested by a large difference between the rigidities of columns and walls of the cella.

After we familiarized ourselves with the standard antiearthquake techniques, let us find cases where the Greeks had to seek nonstandard solutions to see their ingenuity.

Peripters, rectangular buildings having a peristyle with a single row of columns, were the most popular style of Greek temples. At the same time, there existed round peripters and other edifices. According to the writings of Homer, a tholos (which means a round house) was erected in the yard of the palace of Odysseus. The ensemble of the Asclepius shrine on the peninsula of Peloponnese included a tholos, or a thymele, built by Polycletus Junior in 360-330 B.C. This was a round edifice, about 29 m in

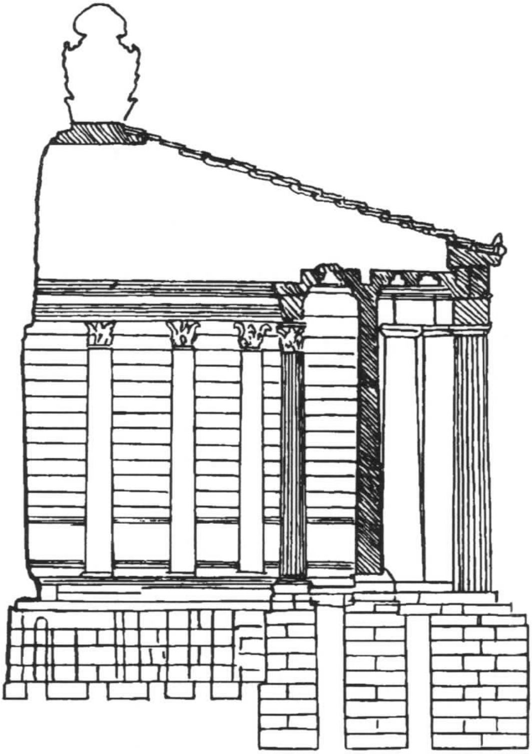


Fig. 38. Separate foundations of thymele temple in Epidauros, the 4th century B.C.

diameter, surrounded on the outside by 26 columns of the Doric order, which had inside 14 columns of the Corinthian order, the third Greek order in architecture (Fig. 38). The purpose of this building remains unknown. From the standpoint of seismic stability, its planning was more perfect than that of a rectangular building. Its symmetry may be said to be ideal. The foundations were deep closed rings, separate under the outside columns, the walls and under the inside columns. This once more points to the fact that the Greeks designed their structures so that they were ductile. Found under the central floor were a few concentric walls left from an earlier structure. The foundations of the outside columns and wall had a common top binding. The result was that the building was divided, as it were, into two independently deforming rings. Those were an inner ring that comprised the inside colonnade bound by a girder at the top and the foundation at the base, and an outer ring formed by the wall and external colonnade also bound on the top and at the base. The stone slabs laid on the inside and outside colonnade walls had coffers to essentially reduce the weight. It may be assumed that the roof was also either light or wooden, or was absent. This edifice did not survive, and what destroyed it I could not find out. But from the standpoint of seismic stability of that time, this building practically had no shortcomings.

It is interesting that in constructing most ancient temples the Greeks were aware of the importance of a strong base under them. The temple of Hera, dated the 8th century B.C., was built on the same peninsula of Peloponnese, in Olympia. This temple was constructed on bad grounds deposited by a mountain river. As a result, the base rock was bedded deep, while the surface strata were clay quick grounds with underground water close to the surface. Besides, these areas were known for frequent earthquakes. The temple of Hera was erected on a special man-made platform (stage) built on closely driven piles, the space between which was packed with crushed stone and pebble.

The slabs of the temple wall base were laid on this stage, and the temple walls of air-dried bricks with timber frames were then erected on these slabs. The columns, beams and load-carrying parts of the roof were first made of timber. The roof was covered with clay tile. Despite the fact that it has been built of short-lived materials, this temple existed for more than a thousand years, till the 4th century A.D. The temple was frequently and carefully repaired with timber columns replaced by stone ones.

This was not the case with another temple, the 4th century B.C., that was built in the honour of Athena, on the peninsula of Peloponnese. This temple was destroyed because the builders failed to implement the earthquake-resistant techniques of that time. Its very shallow foundations were laid in weak alluvial soil for the whole temple without reinforcing the elements under heavy vertical loads. Only some of the stones were tied to each other by metallic fasteners. Because of this, the masonry joints broke apart everywhere due to stone blocks sliding during an earthquake. The top portion of the building collapsed and produced deep hollows in the stone floor. The builders obviously did not use the abundant experience of ancient antiearthquake construction. The ancients behaved, like we do, ignoring the heritage of the past and not taking into account the experience of today.

I recall the following. A few days before the catastrophic earthquake in Armenia, 1988, a meeting was held in Ashkhabad in connection with the fourty years of the Ashkhabad disastrous earthquake. Many specialists in the earthquake-proof construction were present, mainly from the Central Asia regions. In the course of that representative forum, a local specialist took the floor several times. It was cri de coeur. He wanted to draw the participants' attention to a disgrace and counted on some help of the forum. The matter was as follows. At that time a large building of a department store was being erected in Ashkhabad, and it was known that part of the building stood on a dense basic ground, while its other part on alluvial soil, on the bank of a small river buried by this soil. The nonuniformity of the ground was indicated by the rails of a tower crane that was utilized in the construction work. The rails ought to be raised at one end every week as the crane came down towards that end because of soil settlement. The building also settled nonuniformly with cracks appearing in it already at the construction time. It would lead merely to a failure in the future, especially in such seismic an area. It seems to me that this fact was neglected. A general conclusion to be made from this fact states that the ground under a building must be homogeneous, as well as the building itself, otherwise specific measures are to be taken.

Many words can be said about the wonderful edifices of the Greeks that perfectly embodied the ideas of comprehensively developed personalities. More than 23 centuries have passed ever since the Epidauros theatre was constructed under the supervision of Polycletus Junior. Even now its preservation amazes us, though this structure is based on soft ground. It is situated in a bed dug on a hill slope in a highly seismic area. The theatre is a fairly flat and elongated structure whose plan somewhat exceeds semicircle. Till now the theatre is free from hollows associated with ground settlements or bulgings caused by landslides during earthquakes. All this is accounted for by well thought-out construction and design and good workmanship. From the present-day viewpoint of supereconomical construction beyond the brick of reason, the construction of this theatre displays exceeding amount of earthquake-proof measures. First of all, the auditorium has a common binding on all sides. This is a strong wall along the external circle, while strong supporting walls are made along the side walls of the auditorium. The ground bedding for the whole structure is thoroughly prepared. Massive blocks of the masonry are connected by horizontal and vertical cramps and dowels. Well-done runoffs and catch basins for rain water add to the earthquake resistance of the theatre edifice.

I think that enough was said about the ancient Greek edifices and their phenomenal qualities, the more so, it is beyond the scope of our book. Our task is to show those structural measures that were used to ensure the resistance of ancient Greek buildings to earthquake effects. These measures are the following, in accordance with the limited number of above examples.

First of all, an earthquake-proof measure is represented by the fact that the ancient Greeks employed only the beam-prop designs in terrestrial buildings, rejecting any elements that produce thrust, such as arches and domes adding weight to the structure.

Next, most of Greek temples feature the symmetric layout of masses (weights) in compliance with their geometrical symmetry. The temples are either rectangular, or sometimes round.

The temples have seismic stability belts at the base and top levels. The base binding is made as a hard-stone stylobate of large blocks connected by metallic fasteners. The columns are supported directly by the stylobate. The top binding can be called double. It is made in the form of cramp-connected beams known as architraves that span from column to column and the other part of this binding is at the roof level along the cornice. As a result, there is a closed framework system.

The next earthquake-proof measure consists in that a structure comprises stone blocks accurately fitted to each other and connected by metallic cramps and dowels sealed in place with lead. Contacting surfaces of the blocks are thoroughly dressed to improve friction. Thorough fitting of the blocks adds strength to the masonry, preventing local concentrations of stresses, hence damage, while the increased friction between the blocks reduces the shaking amplitude of the whole building. The function performed by metallic fasteners sealed with lead was already discussed.

Besides, we must mention thorough compacting of the ground bedding and foundations made in the form of separate elements under the vertical supports. Nonuniform settlements in such ductile systems cause no stresses.

Other seismic stability measures of less importance may also be mentioned. Examples are reinforcement of building corners, some inclination of columns inward for better stability, etc. But all said is enough to convince us that the ancient Greeks gave very serious thought to the earthquake menace and were well aware of the basic rules of earthquake resistance construction.

Now we shall visit some Greek settlements where local building techniques were well combined with Greek construction traditions. Certainly, we shall pay attention to Greek towns in the Black sea coastal area some of which are now on the territory of this country [11, 13, 14, 15].

Greek Settlements

Many settlements were established by various cities of the mainland Greece on Sicily and in the south of Italy. The city of Syracuse located in southeastern Italy became the centre of the western part of the Greek world. Other large cities, such as Poseidonia, Selynunt, Akragant, were situated in the same area. All these settlements were named Great Greece which reached the flourishing of economy in the 7th-5th century B.C. Immense riches accumulated here and enterprise of representatives of Greek tribes that arrived to this area told upon the architecture in this region. Temples, very similar to those of mainland Greece, were mainly built. Most of these numerous temples that survived through different wars were ruined by earthquakes. However, 3 or 4

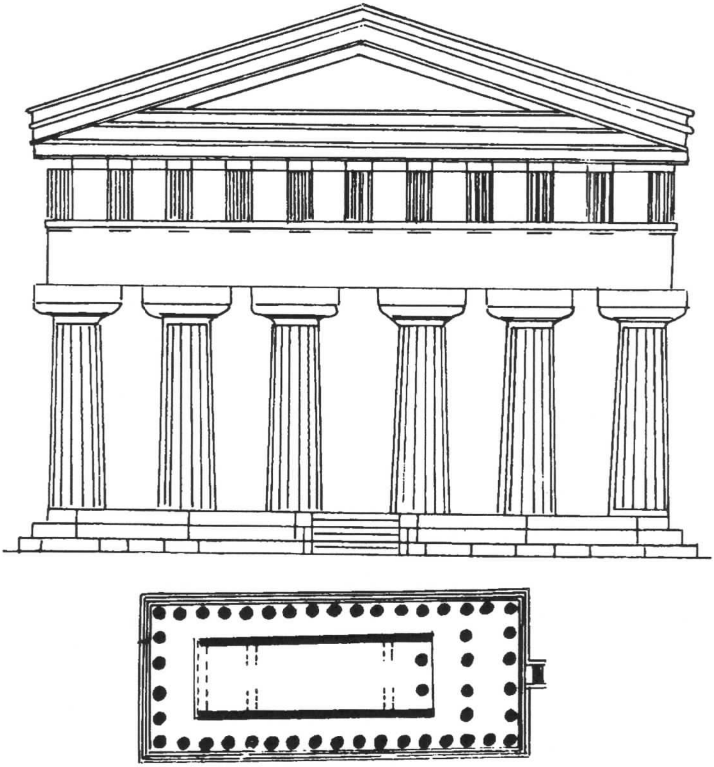


Fig. 39. Gigantomania in the temple of Apollo (frontal view, plan)

temples still remain in good condition, which points to their high resistance to earthquake effects.

I want to draw your attention to two specific features of the local architecture. First, the predominant use of the heavy Doric order. This "courageous" order, probably, well agreed with the aesthetic taste of local citizens. Moreover, the Doric order was used in exaggeratedly weighted builds. The second feature is represented by the gigantism of edifices that were built. Figure 39 illustrates the facade (front face) and plan of the temple of Apollo built in the 6th century B.C. in the city of Syracuse. This most ancient of the Sicilian peripters was built of sandstone. Referring to the figure, its proportions point to immense weights. The ratio of the column height to its foot diameter is equal to 4, while the height of the entablature (the uppermost member of a columnar structure that rests horizontally upon the columns and extends upward to the roof) is 1/3 of the entire height of the order. Also note the plan of the temple. It shows two rows of columns at the main entrance side. This could affect the symmetry of rigidity distribution with regard to one of the temple axes. There is one more important detail we are concerned with: stone blocks were more often tied by wooden rather than metallic cramps. Sometimes they were not used at all.

Now some words about the gigantomania which, as you know, affects the seismic stability of structures. In 520 B.C. the construction of one of the largest temples was commenced in Greece, in Selynunt. This temple was dedicated to Apollo. It was largest in size compared only to the temple of Zeus at Olympia in Akragant, which was called the temple of Giants, and the temple of Artemis at Ephesus, one of the seven wonders of the world we did not yet talk about. It's easier to fancy the size of these temples, if you know some dimensions. The temple of Apollo was 50 by 110 m in stylobate plan, its portico column height was 16.27 m, the column diameter being 1.9 m at the top and 3.40 m at the foot. Imagine a man near this column, and may be you'll be able to fancy the dimensions of the temple. The columns of the temple of Zeus in Akragant were still greater: 16.83 m in height and 3.48 m in diameter at the foot. Compare these dimensions to those of the columns of Parthenon: 10.43 m in height and 1.90 to 1.48 m in diameter. The highest columns, however, were built in Iran. True, the vertical loads there were far less. The columns in the apadana of Xerxes in Persepolis were 19.5 m high and 1.58 m in diameter. In the apadana of Artaxerxes II in Susa the columns were 20.0 m high and 1.57 m in diameter.

With regard to the height of the two last columns, their diameters were a little small, and it was risky to take this ratio of the column diameter to the column height in a region known for earthquake danger. The columns in the Karnak temple were still higher, 20.4 m, but their height-to-diameter ratio was proper.

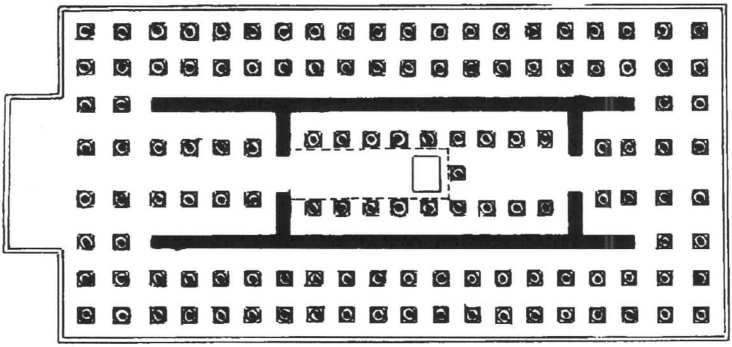


Fig. 40. The temple of Artemis—a multicolumn wonder of the world

If we now set off in the opposite direction, i.e. to the East, into the Greek settlements (colonies) situated along the western coast of Asia Minor and on the adjoining islands, we shall see still worse seismic stability of the structures. Of all the numerous edifices till the 4th century B.C. none of the buildings survived. Neither there remained columns and walls, unless one can find only fragments and foundations.

In order to tell you about the specific features of Greek edifices in Asia Minor, some examples of their structural design will be presented. There are still left four wonders of the world to be considered by us. Three of them are situated here to be used as examples.

The fourth wonder of the world is the temple of Artemis at Ephesus. The construction of this archaic temple was started in the first half of the 6th century B.C. and took 120 years. The first architect of the temple was Hersifon from Knossos. Both the area of Knossos and that of Ephesus featured high seismic activity. The site for the construction of the temple was poorly selected. It was decided to build the temple near the mouth of the river Kaistra where continuous marshes stretched for many miles. Not in vain architect Hersifon proposed that a deep foundation pit be dug for the temple and filled with a mixture of charcoal and wool of animals to make a shock-absorbing cushion.

The temple of Artemis was a dipteral, i.e. it had two rows of external colonnades. Figure 40 shows its plan. The temple dimensions along the stylobate were 109 by 55 m. The total number of marble columns was 127. Their diameter varied from 1.60 m to 1.05 m. The column height was supposedly 18 m. These dimensions demonstrate that the columns were very slender. The multitude of columns produces an illusion of association between the dipterals-temples of Asia Minor and multicolumn temples of Egypt. As a matter of fact, there is an essential difference between them. Standing close to each other, thick Egyptian columns ensure stability of the whole building during an earthquake. This is not the case with the Greek slender-column temples where the columns are spaced at more than 6 m. Such large spacings between the columns indicate that to span such distances wood was widely utilized. This, as is known, was used by Herostratos who burnt down the temple of Artemis in 356 B.C. to become famous. After this the temple was restored several times. Much harm was done to the temple by the Goths who plundered it in 263 A.D. However, the main disadvantage of the temple was in the marshy soil it stood on. Great and nonuniform settlements actually tore the huge temple into parts, the ties between stone blocks being very few. The temple was finally ruined by an earthquake by the end of the 4th century A.D. The remains of the temple saw the sunlight fifteen centuries later, when in 1870 D.T. Wood, the English engineer, excavated the temple remains among musty marshes at a depth of 6 m.

In this locality, on the coast of Asia Minor, in Halicarnassus, the capital of Caria, we can see the fifth wonder of the world (according to our numbering). This is a large magnificent tomb of king Mausolus (a mausoleum). The construction of this tomb was commenced at the time of the king's life and completed after his death, in 353 B.C. (Fig. 41). Its dimensions in plant are 66 by 77.5 m, and the height is 46 m. According to its design, it was a large edifice that combined the elements of Greek and East architecture and was to be used as a tomb and a temple simultaneously.

Let us consider the construction of the tomb of king Mausolus, which was based on dense semirock grounds. Deep ditches were dug in these grounds where large foundation slabs of cut stone were placed. Next was a rectangular, marble-faced high socle of

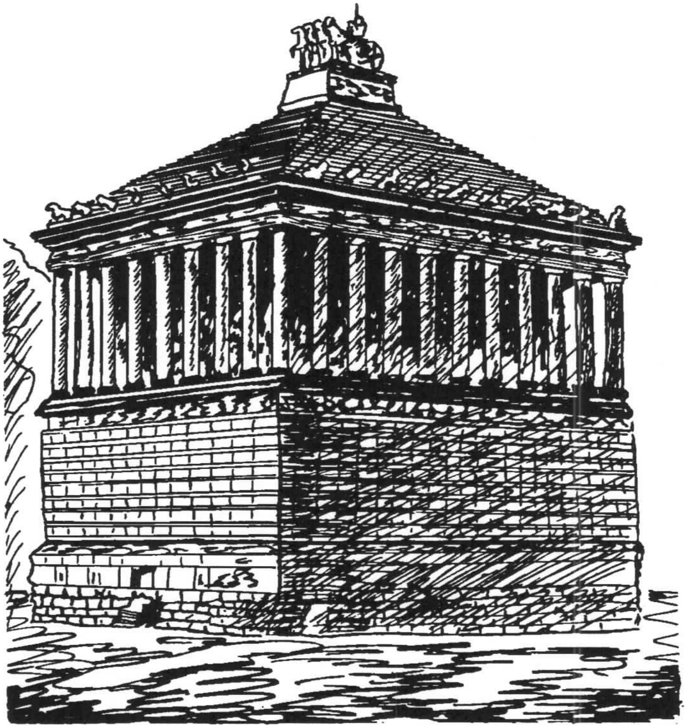


Fig. 41. The mausoleum in Halicarnassus—one more wonder of the world

the edifice. It is assumed that the socle was filled inside with air-dried bricks, i.e. a soft pillow was thus formed under the edifice. The ground floor was occupied by the tomb proper. It was surrounded by a blind wall of marble blocks thoroughly fitted to one another. The blocks were laid with proper bonding of the masonry and tied to each other by metallic cramps. In addition to the walls, the ceiling above the ground flood was supported by fifteen massive columns of the Doric order. The next floor of the edifice was the temple proper. It was nothing more than a peripter with 9 by 11 columns of the light Ionic order. The cella walls in the temple were made of marble blocks as well. There were also

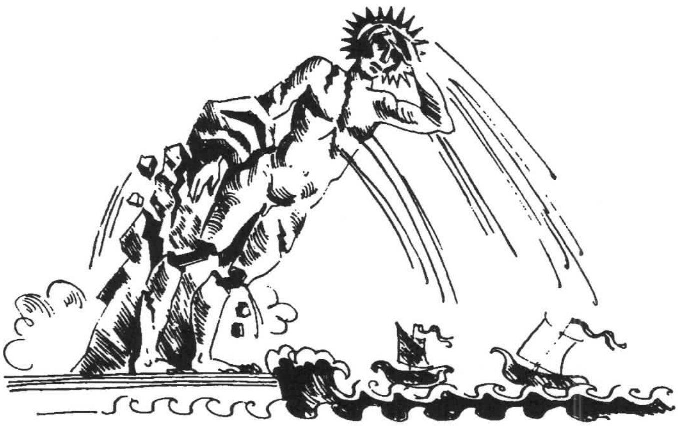


Fig. 42. The colossus of Rhodos—a unique structure

columns inside the cella, which as if continued the columns of the ground floor. The cella's columns and walls, as well as the columns of the external colonnade, supported the heavy roof of the edifice built in the form of a 24-step pyramid crowned with a marble sculpture of a quadriga, a chariot drawn by four horses.

From the standpoint of earthquake resistance, this edifice has two shortcomings: large dimensions and, mainly, a highly raised pyramid-like heavy roof. However, the mausoleum stood as far back as from the 12th century and was ruined by an earthquake in the 13th century. It was finally demolished in the 15th century by the Rhodos knights who used its stones as a building material for fortress walls.

The sixth wonder of the world—a gigantic statue of Helios named colossus of Rhodos was situated not far from Halicarnassus, on the island of Rhodos. The Greeks had the custom of making huge statues, in connection with some event, or in honour of gods. An example is the statue of Zeus, 20 m high, made by sculptor Lysippos. To an order of the citizens of Rhodos, his follower Khares from Lind made the highest statue of about 35 m (Fig. 42). The construction of the colossus took 12 years and was completed in 276 B.C. To build it, 13 tons of bronze and 7.8 tons of iron were consumed. This famous structure lasted for only 56 years. In 220 B.C. the statue collapsed during a severe earthquake because the colossus legs broke under it.

The construction of the colossus was as follows. Three stone poles were installed in the pedestal depth to provide support for the whole structure. The poles were laid of rectangular stone plates secured to each other by iron strips. All the three poles were united to form a single framework to which a bronze shell, only 1.5 mm thick, was secured by means of metallic ties. Two stone poles were laid inside the colossus legs, while the third pole was hidden in the hanging down folds of the mantle. Metallic rods diverged in all directions from the poles being secured in the joints between the stone plates. Iron rims of the required dimension and shape were fastened to the outer ends of the rods, like to wheel spokes. The bronze shell of the statue was then secured to those rims.

As you see, all was done to good reason and skillfully. Maybe, the base was not strong enough to withstand the earthquake. Or settlements under the statue's supports were not uniform, or, most likely, the highly located mass caused such high stresses in the colossus legs that they failed. Several attempts were made to restore the colossus of Rhodos, but all of them proved unsuccessful. The remains of colossus lay on the ground more than 1000 years, until the Arabs, who captured Rhodos in 997, sold them to a merchant who took the remains out on 900 camels.

Let the last, 7th wonder of the world—the temple of Zeus in Olympia—be considered now. The seventh wonder of the world is a statue of Zeus made by Phidias and housed in the temple, rather than the temple itself. The statue was made of gold and ivory. The temple, the largest one on the peninsula of Peloponnese, was built of hard local limestone coated by a thin layer of fine white marble plaster.

By considering this last wonder of the world we have an opportunity to demonstrate the design of a temple in the strict Doric style. The temple was built in 460-450 B.C. Its dimensions in plan were 27.5 by 64 m with the number of columns 6 by 13, their height being 10.43 m. The main information, however, is presented by the cross-section view of the temple (Fig. 43) and the cross-section of the entablature shown in the same figure. First

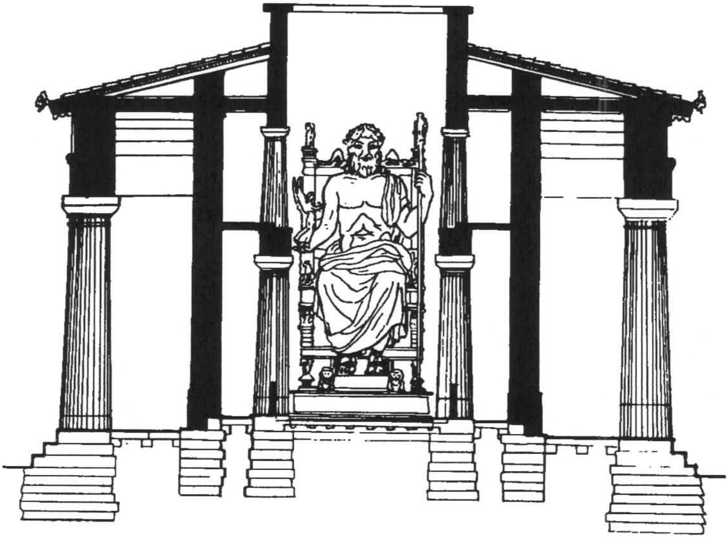


Fig. 43. The temple of Zeus built on poor grounds

of all, separate foundation under each vertical structure indicates that we deal with the beam-prop system. Unfortunately, it seems that the plates of which the foundations had been assembled were thoroughly fitted and tied to each other, and, hence, the plates could not slide with regard to one another during an earthquake. Next, note the load-carrying stone girders-architraves that comprised three edgestanding plates. The component parts were very thoroughly fitted to each other. Well thought out and exact function of each detail can be seen in the temple. The figure also demonstrates some wooden parts of the roof.

Next, we shall visit one more vast region of Greek settlements, i.e. the northern Black sea coastal region. Almost 1000 years, from the 6th century B.C. to the 4th century A.D., there existed such ancient states as Olbia, Chersonese, Bosporus.

The city of Olbia was founded by the natives of Milleta at the beginning of the 6th century B.C., at the mouth of two large rivers Gipanis (Bug river) and Borisofen (Dnieper river). At once, the city gained a leading economic position in the north-west of the

Pontus Euxinus (the Black sea). Already in the 4th century B.C., Olbia built powerful defence walls and towers of rectangular stone blocks, trade buildings, temples, and dwelling houses. At the best wall footings and foundations of these structures survived till our time. I have nothing new and interesting to tell you about these very structures, everything was as usual, but their foundations were specific, the ones we did not yet encounter. The city was built on river depositions and in highly seismic Black Sea area, therefore, local builders started using sandwich foundations. Practically, the whole city, including dwelling houses of rich people, was built on these sandwich foundations.

The technique of making a sandwich foundation was the following. First of all, a foundation pit was dug so as to pass the depositions of ground and to reach the natural dense rock. Besides, as it should be, a sufficiently deep and wide pit was dug to correspond to the structure to be erected. The pit bottom was covered strictly horizontally with a layer of ash, sometimes mixed with coal, from 5 to 15 cm thick. Being wetted and rammed, the layer of ash was then covered by a layer of clay, 10-25 cm thick, which was also rammed. The ash and clay were alternated to obtain the required foundation height. Some time later the clay became permeated with salts contained in the ash to be followed by crystallization process. The result was a strong monolithic foundation able to carry heavy loads produced by fortress walls. Specific strength was featured by the sandwich foundations under the edifices of importance. The foundation layers under the temple of Zeus were laid strictly horizontally with a thickness of 5 to 12 cm for the ash layers and 10-18 cm for the clay layers. It was of utmost importance to use pure ash and clay without rubbish admixtures as was the case with the foundations under dwelling houses where the ash layers contained bones of animals and crocks of amphoras. The purity of material imparted strength to the sandwich foundations. If a pit left by a previous building was encountered in the site where a foundation was to be laid, the pit was completely freed from loose fill, and the foundation was lowered to the pit bottom. For the present, we know sandwich foundation laid up to 4.5 m deep. The foundation width may range from 5.0 to 12.0 m.

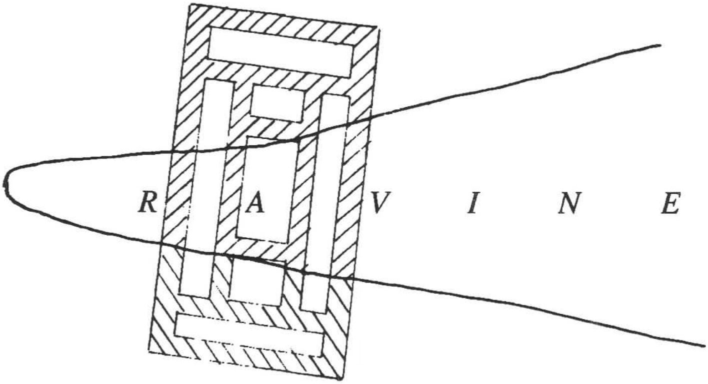


Fig. 44. Plan of sandwich foundation under the temple of Apollo in Olbia

The sandwich foundations of the temple of Apollo Delphinii were distinguished by greater perfection. They were held by well-dressed, edge-wise placed facing plates of limestone that strengthened the walls of the pit dug in loose grounds. Naturally, such a foundation will be much stronger than a foundation simply cast in soft grounds. For the plan of the sandwich foundation of the Apollo temple, see Fig. 44. In compliance with the requirements for the earthquake-proof construction, the foundations formed closed contours. The same contours were formed by the temple walls. Considering the design of the sandwich foundations, a conclusion may be made that ancient builders tried to protect their buildings against nonuniform settlements. Attention must be drawn to the joints between the stone walls of buildings and the sandwich foundations. There was laid a thin ductile interlayer of clay and fine rubble about 5 cm thick. This interlayer provided uniform transmission of the loads caused by the walls to the foundation and formed as if a sliding layer between the load-carrying structure and the foundation. It would be of interest to check whether layers of the sandwich foundation could slide relative to each other.

An example is the northern defence wall, 4.5 m thick. The width of the sandwich foundation was much greater. It was

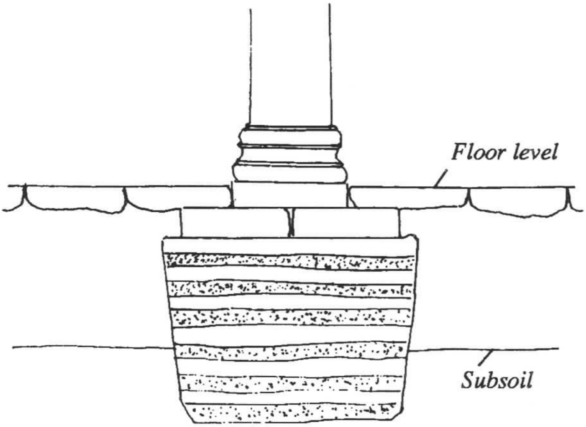


Fig. 45. Sandwich foundation for column

covered with clay mixed with rubble. Placed on this filled layer were four flat stone slabs that formed the base for the defence wall. Note that under the weight of the wall, the central part of the foundation settled, while its edges raised. This points to the fact that the sandwich foundations possessed ductility properties. Figure 45 shows installation of the central column of a large public edifice on a sandwich foundation. The column stands on a plate which, in turn, conveys the load to two plates laid on the sandwich foundation.

To conclude, the following should be said about the sandwich foundations. These foundations might not perform the function of sliding layers during an earthquake, but, beyond any doubt, they were strong and monolithic for edifices built on weak grounds. Besides, their dense nonhomogeneous structure well dissipated and reflected the earthquake waves.

Before leaving Olbia, I believe at least one example of its burial architecture must be considered. No ground burial edifices of Olbia have survived, while underground ones are not few. We are interested in studying the burial edifices because they were built, without sparing means, for rich people. Their long service life was planned, for which reason most advanced ideas of that time were implemented in these edifices.

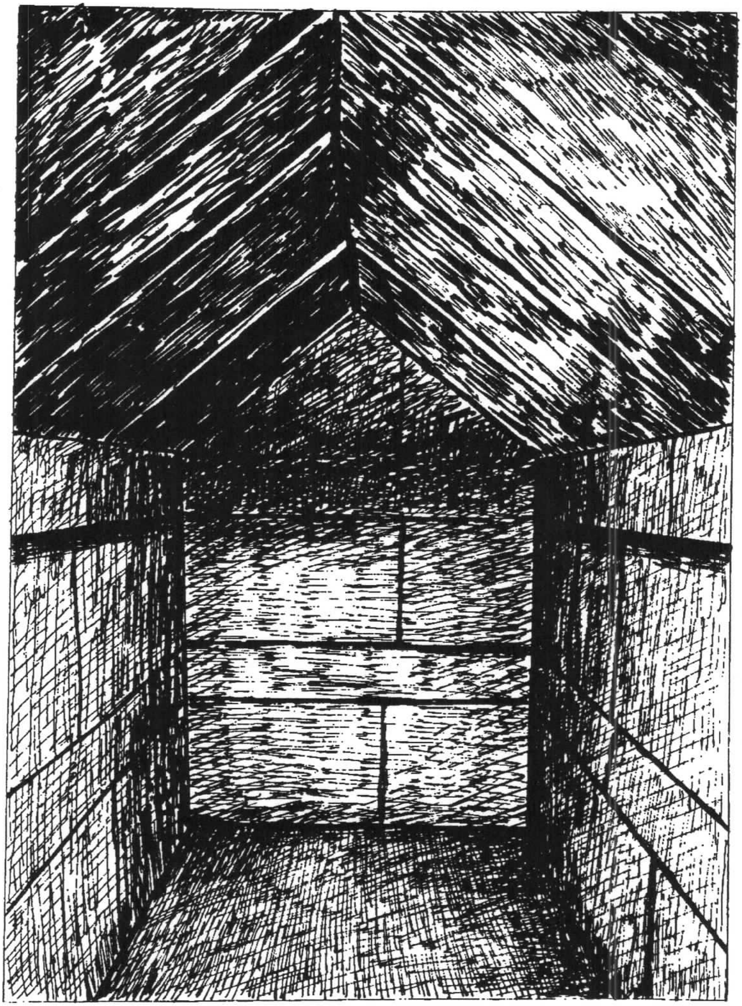


Fig. 46. Stone tomb—a sample of design perfection

In 1911 B.V. Farmakovskii found a stone tomb in a mound, which was rectangular in plan with a gable roof (Fig. 46). Its dimensions in plan were 2.75 by 1.40 m, the wall height, 1.40 m, and the height to the roof seam, 2.35 m. The burial vault was laid of bulky, thoroughly dressed and tightly fitted limestone plates. The walls were laid of four tiers of plates. The first and third tiers of plates were placed edgewise at the bottom, and in other tiers the plates were laid flat. The bulky plates forming the gable roof were placed obliquely on the top tier of the flatly plates of the wall. There was a joint tongue in the top seam between the obliquely placed plates. Their thrust stops at the lower end were provided on the horizontal plates. In addition, two tiers of flat-laid plates formed antiearthquake belts, i.e. a common binding of the whole structure. The vault was held compressed by ground fill, since a mound was formed above it by piling up earth. As you see, the design of the burial vault is simple, but it features a common concept and well thought out details. In spite of many earthquakes that occurred in the northern region of the Black sea area the vault survived, though it was most likely built in the 3rd century B.C.

In Olbia we familiarized ourselves with the sandwich foundations and mound-covered burial vault, and now we shall leave for another ancient city—Chersonese. This city is known for its magnificent defence ensemble. Let us consider some antiearthquake methods used in the construction of the fortress wall and towers of this ensemble. A rock was utilized as the base for most ancient walls and towers of the southern defence structures. The lower foundation blocks of these structures were not placed directly on the rock. There was a sand interlayer between them whose purpose is known. In case a wall or a tower was erected on an inclined surface of the rock, a horizontal bed was first cut. A thin layer of sand was filled after, and only then the foundation blocks were laid.

As to the wall masonry, the life of Chersonese saw the use of more than one type of masonry each featuring antiearthquake properties. The first type of the Chersonese defence masonry is dated back to the 5th century B.C. The three-layer wall was typical for that time. The external and internal facing of the wall was made of bulky stones, 1.50 by 0.42 by 0.45 m, dry laid along and across the wall. The internal space of the wall was filled with quarrystone bonded by clay mortar. The total thickness of the wall was 2.35 m. The second type of masonry is referred to the 4th century B.C. In this case, the wall was homogeneous and was made of stones approximately similar in size, 1.85 by 0.38 by 0.38 m. The stones were laid uniformly alternating along and across the wall to provide good binding of the entire wall 4.0 m thick. This masonry ensured high strength of the wall. All other types of the Chersonese masonry were, in fact, derived from the second type. Changes were made in the dimensions of stones, rustic stones appeared, pins were added, but the principle of creating strongly bonded homogeneous masonry remained unchanged. There is one more specific feature common to all types of masonry: long stone blocks were utilized. The masonry with strong lime mortar appeared only in our age.

The design of the defence towers was as follows. We shall consider only one tower, the so-called tower of Zenon, having No 18. Like other towers, this one was many times restored and completed. Therefore, this tower alone can demonstrate those masonry techniques that were popular at different times. As to the structure, the Zenon tower comprised a core and three cylinders of stone masonry related to different ages that were successively laid around the core. The core was a very ancient Greek tower erected in this place. Its diameter was 8.95 m. The core masonry lasted well, though the core tower was somewhat damaged, probably by war actions. This masonry was made of large stones dry-laid to form header and flat tiers and tied to each other by wooden ties of the dovetail type. Besides, the ancient core contained a wooden framework that consisted of interconnected uprights and bedstones. Next, probably, a decision was taken to improve the defence by increasing the tower dimensions. A new tower was constructed around the ancient one, which was a cylinder with a wall 1.70 m thick. This new tower was built in a dry manner of large stone blocks, but without employing wooden ties. It is of interest to note that there was left a clearance, not by chance, from 8 to 40 cm wide, between the old and new towers. Ancient builders knew that each addition to a building must be done independently to avoid additional overloads provoked by nonuniform settlements of different-time structures. Besides, the clearance prevented the old and new structures from collisions during an earthquake. The tower diameter became 12.55 m after the modification.

The enlarged tower was exposed to an intensive earthquake to get damaged, after which it was to be reinforced. To this end, one more stone cylinder was built around the tower. The wall of this cylinder was a three-layer type: the outside facing tiers of stone and the inside rubblework of different-size stones on a strong lime mortar. The purpose of this second monolithic layer was to reinforce the tower, for which reason it was laid without clearance between it and the first cylinder. In 480 a new intensive earthquake took place in Chersonese. To reinforce and restore the tower, a third cylinder was built around it. Actually, the second monolithic cylinder was thickened. To this end, an external facing was erected of large cut stones, while the space between the facing and the second monolithic ring was filled with quarrystone on a lime mortar. Thus, three cylinders of strong walls were built around the main ancient Greek core.

What was the cause of multiple reinforcing the Zenon tower? It was found that it was the poor choice of the construction that mattered, but not hostile assaults destroying it. The tower stood on a rocky slope of the Girlish mountain. Under the conditions of frequent earthquakes, with a deep pit under the tower made in the rock only for the foundation of its core, the tower tended to slide down the slope. Because of this, builders tied all the subsequent additions to the thick defence walls, thus providing supporting counterforts to protect the tower against sliding, on the one hand, but, on the other, to disturb the rigidity distribution symmetry. This led to overloads and relevant damage at points where the walls joined the tower almost squarely.

Other errors can be observed in the defence structures of Chersonese. In ancient times the defence wall between towers 14 and 16 was straight over a distance of 96 m. Being not reinforced, the central part of this wall collapsed in the 3rd century. Builders had to erect tower 15 to create wall support at its centre.

In the Bosporus kingdom, which occupied the eastern part of the Crimea and Taman peninsula in ancient times, we shall consider submound vaults and, particularly, the Regal tumulus.

This memorial edifice located 5 km to the north-east from the centre of the city of Kerch was revealed in 1837 by A.B. Ashik, the director of the Kerch Archeological museum. He said the following about this discovery: "It seems to me that the monument we have revealed is unrivalled in the field of ancient architecture, and if it does not surpass the tombs of Italy, it, at least, ranks among them".

I should like to add that the underground dome-shaped vaults of Mycenae are analogous to this architectural monument.

Figure 47 shows the longitudinal section of the Regal tumulus and the cross-section with the diagonal section of the burial chamber itself. This tumulus was called regal by A.B. Ashik for its huge size and absolutely unique stone construction. The Regal tumulus memorial complex was supposedly completed in the 4th century B.C. for Levcon I. The averaged height of the mound is 18.5 m, the base diameter being about 120 m.

The vault inside the tumulus comprises a chamber and a long, deep entrance passageway, known as dromos, cutting the thickness of the ground fill and reaching the tumulus base. The chamber walls form a square, 4.43 by 4.40 m. They are laid of huge blocks of limestone to form four tiers. The blocks are well chiselled on the face side and accurately fitted to each other in a dry manner. The next is most interesting. The dome-shaped ceiling starts with tier 5. Starting with the corners, massive blocks are projected (corbeled), each tier progressively, thus narrowing the space above the square area of the chamber to form regular polygons by five tiers that develop into a circle with height. Twelve more tiers produce mathematically accurate circles, narrowing progressively with each tier to form a conical dome. The last top circle is covered by a solid massive plate. In this case, an interesting and reliable decision was found in solving the problem of joining the lower square part with the round dome-shaped ceiling by means of stepped pendentives that form transitions between superincumbent round tiers of the dome masonry. The height of the chamber is 9 m. The rings of the conical dome are assembled of long curved stones. Extending into the darkness, the conical dome marked by concentric circles impresses deeply.

Adjacent to the chamber from the southern side is the dromos, a deep passageway, 36 m long, 2.5 m wide, and up to 7 m high. It is also dry laid of huge limestones thoroughly fitted to each other and forming a corbeled narrow vault. It is assumed that the walls

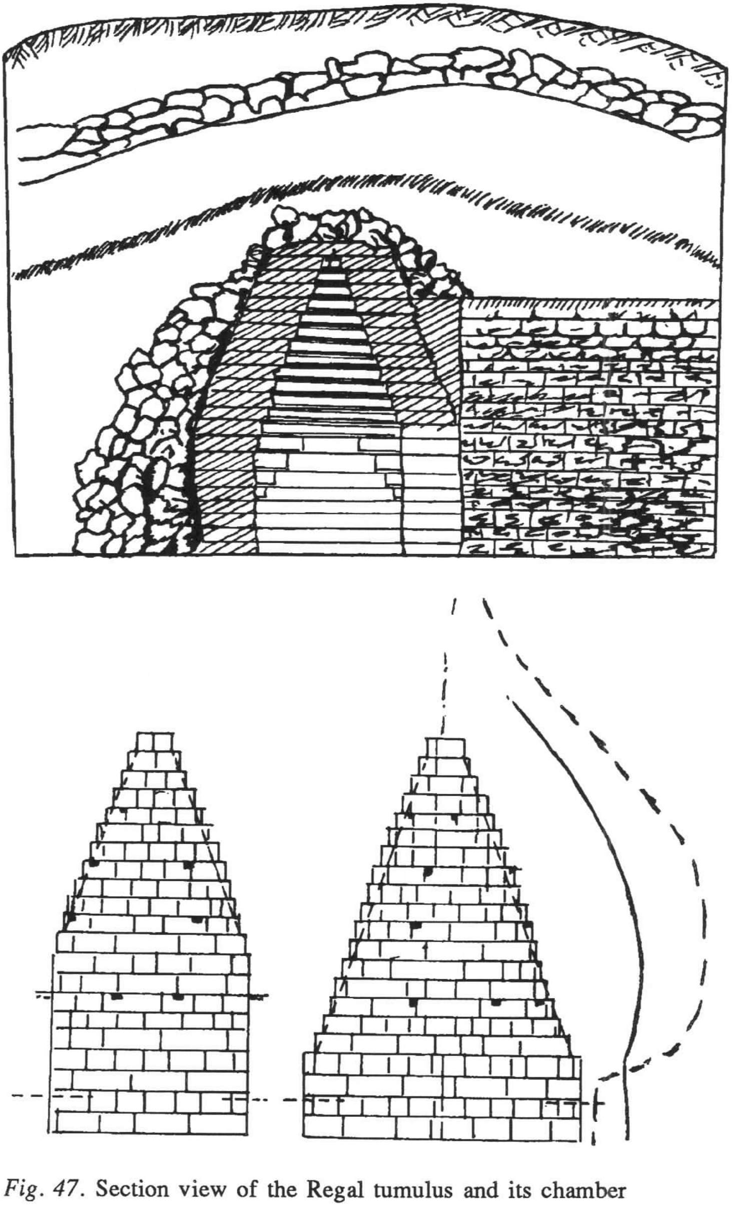


Fig. 47. Section view of the Regal tumulus and its chamber

of the chamber and dromos are laid of more than one row of cut stones, i.e. of two or three. As illustrated by Fig. 47, the chamber and dromos are buried at the outside in large natural stones laid in 6-7 rows at the footing and 3-4 rows over the dome. This nondressed stone material forms as if an arch over the vault, and, taking the load caused by the above-filled ground, performs the function of a corbeled system. The multicourse ground fill of the tumulus is not simple. The first course hardly covers the chamber dome and dromos together with the stone fill. Next, the whole fill is covered by a thick layer of sea grass. This compressed seaweed is very like fir branches. The grass layer is again covered with ground. This second layer of ground, several metres thick, is, in turn, covered by three tiers of quarry stone to form a shell protecting the tumulus fill material against erosion. Finally, the third course of soil piled up completes the construction of the tumulus.

There can be no doubt that the multicourse bulk of the tumulus with the core in the form of a stone vault must be treated working as a single whole from the earthquake-resistance standpoint.

The seismic stability of the tumulus structure, naturally, originates from the vault. Let us consider certain structural techniques utilized in the vault of the Regal tumulus and assess their effects on the earthquake-resistance of the structure.

The burial chamber and dromos are situated on a small natural elevation which later was converted into a mound by piling up ground. The elevation is based on a rock with a flat surface and a gradient of 7 cm per meter. The socle of the burial chamber walls is cut of the rock monolith. The rock under the dromos is levelled with the aid of special substructures so that three horizontal platforms are formed for laying the foundation blocks of the dromos. The substructures are made of wet clay mixed with limestone. With time, the clay became hard as stone, and the result was a kind of a sand-gravel-clay building mixture. Where the platform steps were located, the thickness of the clay layer was 80-90 cm. There are cracks caused by nonuniform settlement of the foundation in such places in the dromos, since the artificial substructures were more ductile than the natural rock. There are no such cracks in the burial chamber, as the blocks were laid directly on the rock of the base. Maybe, it was exactly due to the nonuniform settlements that part of the dromos did not survive till our time and was destroyed by an earthquake.

Now, some words must be said about the joint between the blocks of the wall masonry and the dome as an important element in order to provide the earthquake resistance of the structure. All cut stones of the masonry were dry laid using no mortar, except for the wall existing in ancient times to close the entry to the dromos. Lead was utilized to fill the seams in this wall. The masonry stone blocks were cut of porous and soft Adjimushkay limestone. Its evenly cut surface is porous and rough. Placed on each other and vertically loaded, such stone blocks cannot slide over each other, because the friction force acting between them is too high. It can be explained in the following way. The blocks laid in the wall contact with their interfaces provoking sharp edges of the pore cells to exert pressure on each other. Under the action of the immense weight of the above-lying masonry and the piled up body of the tumulus, the cell thin walls are crushed and penetrate into each other. As a result, the stone block surfaces as if adhere to each other and can be moved relative to one another only after their destruction.

With this simple a structure, the task of joining the round conical dome with the square chamber was solved on the basis of a perfect design (Fig. 48). At that pre-Christian time, the solution of the problem of coupling a dome-shaped ceiling with a square building was a matter of distant future. In this case, the problem was solved in advance. By the way, traces were found in the Regal tumulus pointing to the residence of early Christians. It remained unknown for a long time how they got into it, until a manhole covered up with soil was found.

I was lucky to visit the Regal tumulus and see perfect work of ancient architecture that skilfully combines an architectural problem and its structural implementation. I saw what I first took for spider's web, finest crystals of limestone which facilitate the adherence between the stone blocks.

In order to convince you that ancient builders were very erudite, I will draw your attention to one more detail of the Regal tumulus chamber construction. Look at Fig. 47 showing two cross-

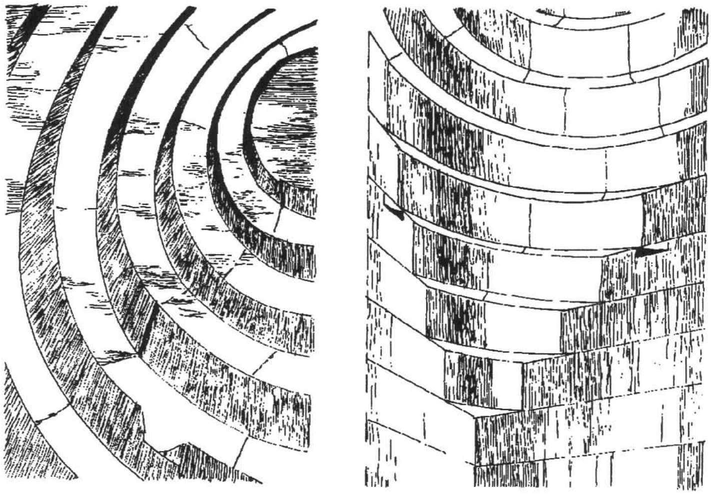


Fig. 48. Rounded joints between square (in plan) structure and round conic dome

sections of the burial chamber. The matter is as follows: the conical or the so-called corbeled dome of the chamber cannot be inscribed into a regular triangle. The actual shape of the dome is shown in a continuous line, to the right of the section view. Why is such a contour made? Whether the ancient builder wanted somehow to correct our visual perception, or whether he wanted to reduce the thrust in the dome. Nobody knows it. By the way, the dome thrust is taken not only by the structural material, but also by the inward pressure of the ground fill. For some reason I associate the complex configuration of the chamber dome with the shape of church bulbs that convey no thrust to the drum carrying them. This shape is shown in Fig. 47 to the right in dashed line and will be designed many centuries later.

There are other enigmas in the construction of the tumulus in question, for instance, the above-mentioned thick layer of sea grass placed in the body of the tumulus. What is the purpose of this grass? Long ago I heard about this layer used in Greek structures in the Black sea coastal area. I didn't believe it was true:

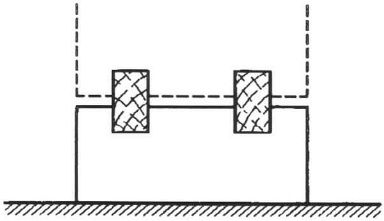


Fig. 49. Seats in temple foundation for fitting wooden spacers

in two thousand years the grass must rot. Finally, I saw these interlayers of sea grass myself. As things turned out, the Greeks and their followers placed these interlayers in the ceilings of almost all buildings. These layers of sea grass last far more than wood. Such an elastic layer forms a sliding surface. Why was it used? Nobody, including very skilled archeologists, could explain it to me. What is a layer of stones in the tumulus for? Maybe, for protection against robbers? In short, whatever the thoughts of ancient builders and their design of the tumulus, their structure was earthquake-proof, which was confirmed by its survival till now.

The structure of the Melek-Chesmen tumulus is approximately the same, but smaller and its dome is stepped and rectangular like that of the mausoleum at Halicarnassus. Further we shall not discuss structures in the Black sea coastal area, but, to save space of the book, we shall just visit those areas and note the details we are concerned with.

If from the embankment in the city of Kerch you will go upward by the beautiful stairs decorated with chimeras and come up the mountain of Mitridat, then turning around its top, you will see the excavation of Pontikapei: traces of ancient walls, towers, reservoirs, water-pipes, including fairly massive foundation blocks of a small ancient temple recently excavated. These blocks have two rectangular grooves along the perimeter, as shown in Fig. 49. These grooves were obviously done to fit wooden bars between the wall and the foundation. The purpose of these bars was unambiguous: to serve as seismic insulators to dampen shocks transmitted from the foundation to the walls in an earthquake. The fact that the city went through a severe earthquake is indicated by

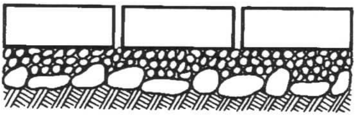


Fig. 50. Preparation of base for foundation blocks

the building walls that fell in one direction and by the displacement fault that crosses the city.

It was said many times, and I will say it once more to fix it in the mind of modern builders, that much attention was paid by ancient builders to the foundation. In the city of Pontikapei, the builders encountered complicated ground conditions in constructing basic edifices. They had to erect buildings on hill slopes of stratified sandstone rock easily giving way to settlements and displacements. The foundations in this city were built as follows. First, a course of gravel sand was laid. Placed edgewise on it were the limestone quadras of the first course thoroughly fitted to each other. The second course of exactly similar quadras was laid on the first course, but this time flat on the bed. The third and fourth courses of stone blocks were laid on bedding of small stones. The first course was edgewise laid to make these blocks better accept bending moment occurring due to unequal settlements or from propagation of earthquake waves. Small stones in the joints between the blocks assist in the uniform load sharing by the foundation blocks, and allow the blocks to slide with respect to each other during an earthquake to, certainly, reduce earthquake loads. To my mind, it was therein that an idea was laid which after more than two millennia has led to the creation of the present-day systems of seismic stability consisting of cast-iron balls or ellipsoids.

Quite recently, the foundations of a large building that might bed a temple have been excavated on the shore of a bay of the Azov sea, in a township named Chokrak. The ruins of this building show traces of the fire, the 3rd century B.C., when a severe earthquake took place in this area, according to the historical data. I saw the method of laying the huge blocks of foundation. It was well seen in the excavation (Fig. 50). The first underneath was a thick course of clay. Then, there were natural middle-size stones. Next, we saw a levelled fill of small stones on which the foundation blocks were placed. The purpose of this construction is clear: uniform distribution of load and reduction of earthquake effects.

Note that no primeval construction techniques that existed in native Greece were employed in Greek settlements. The influence of the East told upon them. For example, lime mortar was used in the above foundation. On the contrary, dry-laid stone blocks connected by cramps and dowels sealed with lead were encountered very seldom. Though, phenomenal examples are found showing that classical construction techniques of the Greeks were known in those areas.

An example is as follows. In 1868 a burial vault was discovered on the peninsula of Taman, in the largest local tumulus located on the hill of Vasyunkin. The vault was called the Large vault. Nearly all antiearthquake techniques known at that time in the West and East were successfully combined in the construction of that burial vault. Figure 51 demonstrates the longitudinal and cross-sections of this vault that consisted of two rooms, an anteroom and a chamber. It is of particular interest that the ceiling was in the form of a barrel vault not used by the Greeks, while the keystones of the vault were connected in the Greek manner by large iron (not a Greek style) cramps sealed with lead. Three transverse stone walls served as the diaphragms for the barrel vault. Laid in the walls were long interconnected stones utilized as the antiseismic belt of the structure to compress it and take up the thrust produced by the vault. This structure was about 4 meters wide and about 5 meters long. As you see, the dimensions of this burial vault were moderate, all was symmetric, its weight might be a bit great, but the whole structure was situated in the tumulus and ground fill compressed it around. Anyhow, the burial vault survived not less than two millennia withstanding all underground storms until it was found by investigators.

Let us talk about neighbours of the Greek settlers, mysterious Scythians with their steppe burial-mounds, indomitable nature, and gold articles in the "animal style". To see them only as dashing cavalrymen would be a mistake. They had their own political

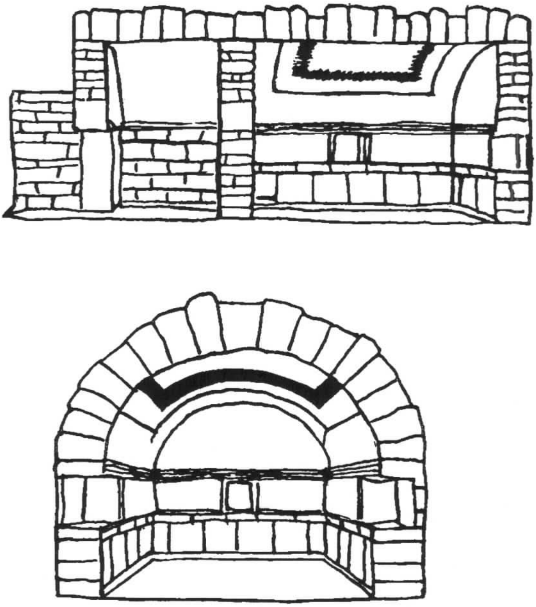


Fig. 51. Burial vault built using construction techniques of the West and East

system, towns, and skilled craftsmen and builders who had a good understanding of antiearthquake techniques. There existed a city named Scythian Naples, near the modern city of Simferopol, whose excavations in 1946 discovered a stone mausoleum which apparently belonged to a famous Scythian king Skilur who lived in the 2nd century B.C. There is no need to repeat the words about high seismic activity of the Crimea peninsula. This was known even by the Scythians who allowed for it in their structures erected after they had settled. Houses were built in place of yurtas and urban mausoleums above the graves of great warriors instead of steppe burial mounds. The list of aseismic measures taken in the walls of the mausoleum is as follows. The stones were laid with bonding; one or two stones were laid longitudinally with the next stone edge-placed crosswise. Thick clay mortar layers were utilized to make the rigid stone masonry ductile, a property already known to you. Finally, to provide reliable bonding of the longitudinal and transverse walls, Γ-like stones were placed in the mausoleum corners. We have not yet encountered such stones anywhere. The walls, up to 1 m wide, stood on a foundation of quarry stone. The depth of foundation was not great, up to 0.4 m, but again, as was the case with ancient builders, the foundation was not in contact with the rock and stood on a thoroughly levelled ash layer. Wood was widely used in the mausoleum, mainly in the structure of the flat ceiling and in reinforcing the upper part of the walls made of air-dried bricks.

Now, following the time spiral, we shall move further, naturally, to Rome to which "all roads lead", though to my mind, it would be more correct to say that all roads lead to Greece. Greek culture contributed much to the world, from philosophy and architecture to sport. The Greek heritage is studied and will be studied ever with many benefits for the mankind. Its architectural monuments that carry traces of earthquakes they were subjected to must be studied as well. This will help us in constructing the up-to-date earthquake-proof structures [13, 16, 17, 18, 19, 20].

Rome
And
Byzantium

Vaulted Structures and Rome Concrete

The history of Rome is conventionally divided into two large periods: the republican from the time of banishing the Etruscan kings in 509 B.C. to the origin of the Roman Empire in 27 B.C., the imperial till the transfer of the empire capital to Greek Byzantium by emperor Constantine at the end of the 4th century. Our task in this chapter is very simple. Without considering any historical origins and development of the construction techniques in Rome, we shall make a short report on how these techniques influenced the earthquake resistance of Roman edifices, and what measures were taken to particularly improve the seismic stability of Roman buildings. However, I would like to say a few words about the influence of the state structure on the construction techniques.

Regardless of whether it was a republic or an empire, the Roman state structure was characterized by its ability to organize and govern. The Roman state had a large army of soldiers, who could be employed in public work, and vast numbers of slaves, who could be made carry out huge volumes of unskilled, most hard work. Besides, victorious conquests helped the Romans to accumulate vast riches and resources using which any large-scale jobs and expensive construction materials could be paid for.

This was the political and economic basis on which the Roman construction techniques were formed. First of all, the Romans almost declined quarrying materials needed for making large parts.

The transportation and processing of such materials called for specific mechanisms and skilled labour of bricklayers. This could be ventured only by the Greeks, nearly each of whom was a skilled craftsman or artist. In exceptional cases, however, the Romans erected structures, similar to Greek ones, of large stone blocks dry-laid and tied by dowels and cramps. They knew how it was done, since their conquests allowed the Romans to appropriate both wealth and knowledge. But usually the Romans made use of another method. With the aid of a large army of unskilled workers the Romans prepared vast bulks of fine construction materials, such as stones, bricks, rubble, sand, lime under the supervision of overseers. Then, the edifice was built under the guidance of several professionals and an architect. Many monotonously repeated operations were carried out, the bricks of facing walls were laid and the gap between the walls filled with concrete and stones. Then, a centering of wood was erected, and the domes were solidly filled with concrete. As the next step, the erected edifice was decorated by facing with beautiful materials and decorative columns. That was the construction technique of the Romans.

Viollet le Duc used the following figure of speech to show the difference between the Greek and Roman buildings. He said that the external architectural forms of Greek buildings are inseparable with their structure, for which reason they can be compared with the naked human body on which you can see the destination of each part. The Roman building resembles a human being who wears a toga that covers and drapes the structural parts of the body.

Speaking of the Roman construction work, we have no choice, but recall Roman architect Vitruvius, the first century B.C. He wrote a comprehensive treatise on architecture, *Ten Books on Architecture*, where Vitruvius gave most diverse information about that time, including recommendations on how and what to build, how to select mortars, construct foundations, erect defence towers, and charge a catapult. Unfortunately, he said nothing about construction of earthquake-proof buildings, and we have to look into the problem by ourselves. Vitruvius has much to be learned from even by the contemporary builder. There are many pieces of useful advice in his famous treatise. The construction technology itself of that time is of interest. We shall not be far out in saying that only we try to construct efficiently and cheaply. In construction the Romans ensured strict saving of materials and financial resources, but they had to build forever , which they did. Reading the work of Vitruvius, one can get to know lots of interesting hints on determining the quality of building materials, or selecting the ground base for construction, as good as we do by utilizing different instruments. There is a simple example. In winter, 1988-89, I had to examine the after-effects of the Armenian earthquake. I saw the sand that had been used in construction. In many cases, the sand was contaminated with clay or soil forming dusty or tufaceous sand. The other components of the Armenian concrete were neither properly selected. The results are known. The construction elements of this concrete not just failed but crumbled to fine pieces and dust, unlike the structures of strong Roman concrete that fell apart into large blocks. Certainly, the Romans would never use contaminated sand for preparing the concrete. They tested the sand in a very simple way. It was poured on a clean white cloth and then shaken off. Traces on the white cloth indicated a poor sand unfit for use. Selection of a ground base for a building is another example. Nowadays, we must carry out ground ringing operations, producing the necessary ground oscillations by explosions or impacts of a cast-iron ball with subsequent recording of these oscillations for analysis using special instruments. The Romans did the same, but in a simpler manner. They placed a bowl filled with water on the ground and threw a stone not far from it. If the water in the bowl oscillated, the ground was considered unfit for erecting a monumental structure, but if they had to build in that site, they removed the weak ground to the bed rock and replaced it with proper material. This will be discussed later.

Thus, the age of Roman building technology was characterized by two new elements: the invention of a new binding mortar and creating a substance known as the Roman cement, and the use of vault ceilings formed like domes and barrel vaults. That turned out to be the very condition for employing vast numbers of unskilled labourers and small-size materials. It would be incorrect to say that the Roman cement was invented by chance. As a matter of fact, even the Etruscans already utilized puzzolan sand as a binding material in erecting vaults. A chemical reaction took place, when volcanic dust from Vesuvius, lime solution, sand, and stones were mixed after adding water. The result was a highly water-resistant artificial stone. Thus, a new age in the building technology started, and it became possible to erect cast structure. And what is more, in compliance with the prestige of the Roman power, it was necessary to erect buildings with large-span ceilings, and at that time such ceilings could be made only with the aid of domes. However, to build such a dome with curved surfaces of block rubble material was a complicated job to be performed by skilled craftsmen. It was much easier to cast domes, and the Roman specific buildings appeared. After the problem has been considered in principle, we shall deal with details.

For the first time the arch-vaulted structural principle and the concrete technology were joined together on a large scale in the Aemilia portico, 174 B.C. With such a fine name, it was a grain storehouse in the port of Emporia on the Tiber river. The dimensions of the storehouse were 487 by 60 m. It comprised 50 separate sections, each having a barrel vault, 8.3 m in span (Fig. 52). The walls of the building were made of very good cement and faced with stone, and the ceilings were made of the same material. We are interested in the Aemilia portico because of several points. The fact that this structure had marked the appearance of typical structures is not of much interest from the standpoint of our subject. That ought to happen under the Roman organization structure in which there were an efficient machinery of management, vast numbers of unskilled labourers, and a few skilled architects. We are much more concerned with the advent of the Roman monolithic concrete. Is this good or bad from the standpoint of seismic stability? Certainly, it is good, though the material is somewhat heavy which Roman builders understood, and later we shall see how they tried to lighten it. However, the buildings of that material were strong with uniform properties, and the more so, if the structure was symmetric with regular distribution of weights and rigidity, the result was an earthquake-proof building.

Next, a structure of monolithic concrete will, for sure, possess properties that differ from those of Greek temples made of stone

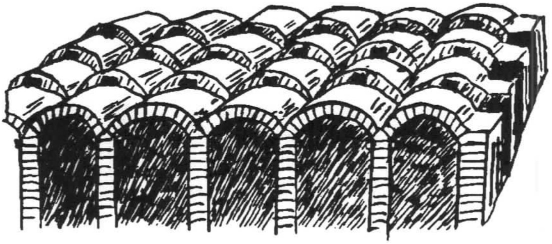


Fig. 52. One of the first cast structures—the Aemilia portico

blocks connected by ductile ties. The Roman buildings will be absolutely rigid, while Greek structures will feature ductility. Strange as it may be, but ancient builders took it into consideration in laying the foundations. In Greek temples the foundations were made independent under the load-bearing vertical elements of a building, and unequal settlements of those foundations caused no overstresses in the ductile structure of a building, while in the Roman rigid structure working as a single whole such foundations could not be allowed. In the latter case the foundations must also work as a rigid whole. Thus, a new type of foundation has appeared. But let it take the normal course.

Like today's builders in highly-seismic areas, Roman builders attached much importance to the selection of ground conditions in planning construction work. According to Vitruvius, an architect at the time of Julius Caesar, bad, weak grounds must be removed to the bed rod and replaced with a strong bedding. An example is the basilica of Julius Caesar in the Roman forum (54-46 B.C.), a rather large edifice, 36 by 100 m in size. This basilica was built in a site with extremely unfavourable ground conditions. It was situated in the lowest water-logged site between the Palatine and Capitol hills, the eastern part of the building being located above the underground sewer—the Cloaca Maxima. In the course of preparing the bed for the structure, builders had to remove the floating earth-clay soil by digging to tuff rock, bypassing and reinforcing the Cloaca Maxima. Thus, eliminating ground defects under the building represents an earthquake-proof measure. The weak ground materials removed were replaced with a man-made substructure that was a stone platform reinforced with timber poles. The platform served as the base for a huge heavy building comprising arch-spanned abutments. The basilica of Julius bears traces of many earthquakes it underwent. Its plinth wall shows shifts and projections of huge stone blocks. Numerous cracks and defects in the building upper part testify to the shaking loads the construction underwent during earthquakes. There is one more curious example of reinforcing the ground base under a building.

Beyond all doubt, the cast concrete technology using facing materials is best represented by the Flavian amphitheatre in Rome (69-96 A.D.), the so-called Colosseum. The Flavian amphitheatre is interesting in that it withstood many earthquakes that frequently occurred in Rome, which was not the case with many other buildings. However, Colosseum suffered much from people who made it a stone quarry.

The plan of Colosseum appears in Fig. 53. The Flavian amphitheatre is a vast oval ring, 156 by 189 m in area, and 49 m in height, with an arena in the center. The structure stands in a depression with weak alluvial grounds. In order to lay a strong man-made base, according to the Roman rules, a pit had to be dug with removal of floating soil to a depth of 12-13 m in an area greater than the amphitheatre itself. The removed ground was replaced by a whole system of substructures which were to support the huge mass of the building, movable crowds of spectators up to 50 000 people, and to make the whole gigantic ring stand without failure to an earthquake and work as a whole.

I could not find the data on the underground structure of Colosseum, and it is unknown whether this information exists at all. Some information, however, has been obtained. First of all, the substructures are known to be laid under Colosseum, and their design was successful. This is indicated by many traces of earthquakes Colosseum went through, but collapsed load-bearing structures were not observed. In contrast to Colosseum, imperial forums failed shortly after their construction, because they had no common cast substructures.

It is also known that the substructure system of Colosseum included the following two structural elements: a wall system of limestone and travertine on a lime mortar to form the upper part of the substructures, with the lower part in the form of sandwich

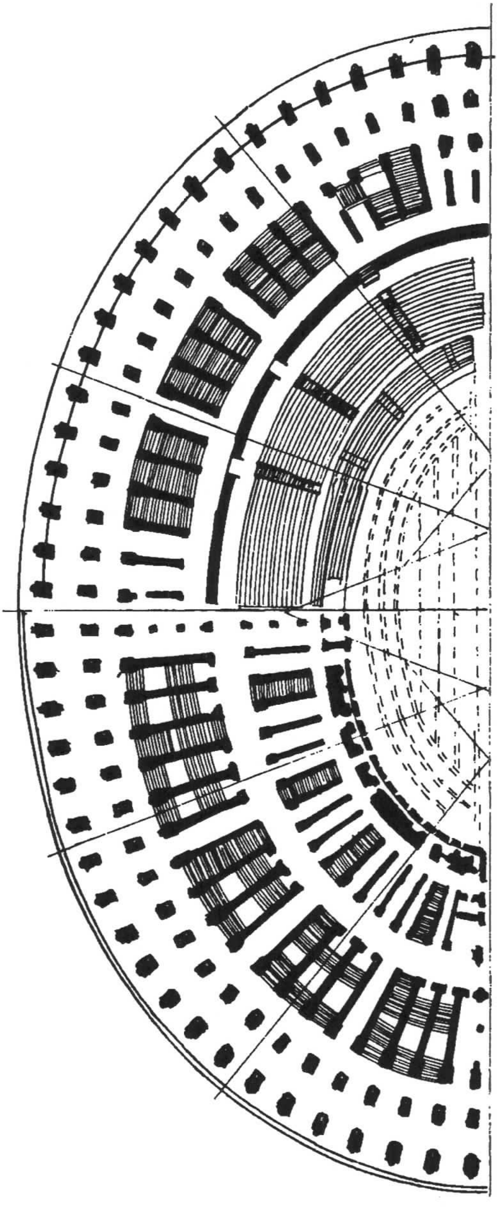


Fig. 53. Plan of Colosseum—embodiment of structure regularity and symmetry foundations, as we may call them. In more detail the matter is as follows. There are two methods of erecting cast structures in the Roman building practice. The first method is "monolithic" and consists in a continuous concreting without ramming. Each 3-4 cm course of mortar is charged with coarse aggregate. This produces a fairly strong homogeneous monolithic medium. This method was used in concreting the dome of Pantheon to be discussed later. The other method consists in creating sandwich structures. To this end, if required by the project, 0.10-0.15 m courses of lime-puzzolan mortar are laid either in the walls between the facing stone blocks, or in the foundations. Then, a course of fine aggregate of about the same thickness is added to it. As the next step, the resultant course is rammed and sprinkled with fine granular material and dust. Due to stone dust, sandwich walls or foundations consisting of firm slabs and ductile layers between them are erected. Being shaken by an earthquake, these slabs can slide with regard to each other. This reduces the motion transmitted from the ground to a building in an earthquake. Besides, no stresses accumulate in such a sandwich body owing to concrete settlement. Here you have one more idea that was implemented 2000 years later in the form of earthquake-resistant slide belts. The man-made base of Colosseum includes such sandwich structures which, probably, contributed to its seismic stability.

The aboveground parts of Colosseum do not deserve a detailed discussion. These are sound conventional structures consisting of load-bearing walls radially laid and reinforced by abutments. These walls are interconnected by arched-vault ceilings, a system of galleries and passageways. In short, the whole structure is an integral strong body in which the rigidity and weights are uniformly and symmetrically distributed with regard to the axes of symmetry. As a result, Colosseum was erected as an earthquake-proof structure. This was ensured by correct configuration, the use of vaulted structures of cast concrete, as well as by preparation of a ground base and laying the foundation with seismic-stability elements under the whole structure.

Generally, the Romans well knew what foundations must be laid and on what grounds. To prove this, we may take similar structures erected on different grounds and compare their foundations. Examples are temples of Vesta—small round ritual structures. Comparing the temple of Vesta on the Roman forum, which stands on alluvial grounds with a high ground water level, to the temple of Vesta in Tivoli, which is erected on a rock, we see that they stand on quite different foundations. The former stands on a cube-like deeply laid substructure borne by the bed rock, while the latter is located in a hollow man-made in the rock and filled with sand. Note that ancient builders never erected buildings directly on the rock, as we do. They used seismic insulation of sand or clay without fail.

A few words must be said about the evolution of the Roman construction technology. In the 5th-3rd century B.C. the Romans widely used stone in the monumental construction work, making fairly large blocks of it. First, the masonry was dry laid, and then stone was used as a facing material filling the internal wall space with rubble fill mortar-bonded. At the end of the 3rd century B.C. the Roman cement appeared, and in the 2nd century B.C. burnt bricks were popular. Ever wider applications were found by the construction technology based on the use of small-size materials, bricks and concrete. Columns were laid of shaped bricks, the internal voids being filled with concrete. In Roman Empire the construction of walls and vaults was based on concrete. The brick was substituted for stone as the facing material. The walls that comprised brick facing and internal monolithic concrete bulk featured an increased strength and rigidity. The cast domes were also highly rigid. To impart some ductility to the domes and walls, Roman builders reinforced the domes with brick ribs (Fig. 54). The walls were reinforced by transverse timbers made of burnt trunks of oil-yielding trees. This reinforcing resulted in an equal settlement of the walls and domes. Roman builders were high-level professionals. Here is a simple example.

For a long time I could not understand what provided the uniform settlement and joint work of the brick ribs in a dome and the arches embedded in the monolith of the dome and the cast concrete; otherwise additional stresses would occur in the dome, and cracks would be formed in the material that settled quicker. But there are no such cracks in the Roman domes built of different materials. This means that the brick material and concrete work

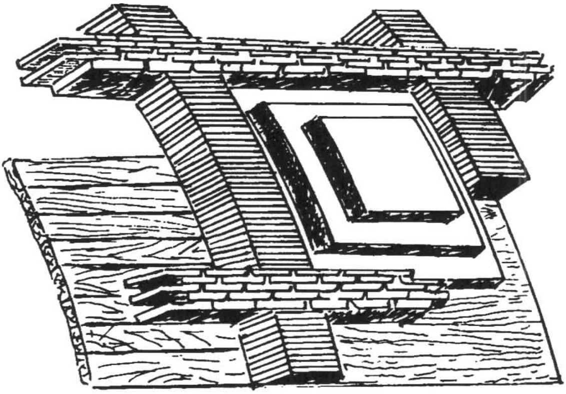


Fig. 54. Brick ribs in concrete bulk—only the Roman construction method

together. How did Roman builders get it? The answer turned out to be very simple. It was necessary to count the number of concrete batches in order to provide an equal volume of mortar in the concrete body and in the joints of brick arches. The result would be an equal settlement in the domes and the absence of stress concentrations. Thus, as far back as 2000 years ago, such difficult construction problem was solved by providing equal quantities of mortar [13, 21, 22].

As the next step, let us proceed to a detailed consideration of such an important element of Roman structures as domes.

Domes of Rome

All building structures can be divided into two large groups by the type of ceilings used. The first group includes buildings where the girder-pillar system was employed. An example is Greek temples discussed above. We began studying the second group of structures while considering the construction techniques in Mesopotamia to be continued in this chapter. These are the structures where ceilings are made in the form of arches and domes that provoke an outward thrust transmitted to the walls and columns. In this case, the structures bearing the dome-shaped ceiling must be additionally reinforced. Other problems arise as well. It is natural and easy to join a spherical dome and building walls laid in the form of a cylinder, but how can it be done when the dome is round, while the walls form a rectangle? How can the dome loads be uniformly transmitted to the walls to avoid stress concentrations and overloads? It is of utmost importance from the seismic stability viewpoint. Earlier, we acquainted ourselves with the good joining of the dome to the walls in the Regal tumulus, and we shall see later how it can be done, since this is our problem.

Generally speaking, the entire history of dome construction can be represented in terms of the drive for improving dome joining to the walls and reducing their weight and outward thrust.

There is one more question. Once we are going to familiarize ourselves with the domical system of roofs, it will be wise to make their general evaluation from the standpoint of seismic stability. One more principle saying that "the simpler the structural scheme of a building, the better is its seismic stability" must be added to the seven principles of earthquake-proof construction formulated at the very beginning of our study.

Certainly, the use of domes makes the building more complicated, causes additional forces in the form of a thrust, and, thus, needs additional inert masses to take up the thrust loads. Besides, on account of the dome height, which is often raised on a high drum, the centre of gravity of the whole structure is raised. All this is not good. On the other hand, however, the use of domical roofs plays a positive role. The dome itself is a symmetrical structure, and, hence, when the building spanned by it is well designed, the structure bearing the dome must be symmetrical. Naturally, it is logical to construct a round building under a round dome for the masses and rigidity to be uniformly and axisymmetrically distributed. This is an ideal case of the building planning from the standpoint of seismic stability. Various round structures are known in the history of architecture at all times and in many peoples. Now we call such buildings centric. These are tombs, temples, combat towers, and many others. Many centric buildings were erected by the Greeks and Romans. An example of the ideal centric building may be represented by the two-tier barrel mausoleum of Helene having a domed vault

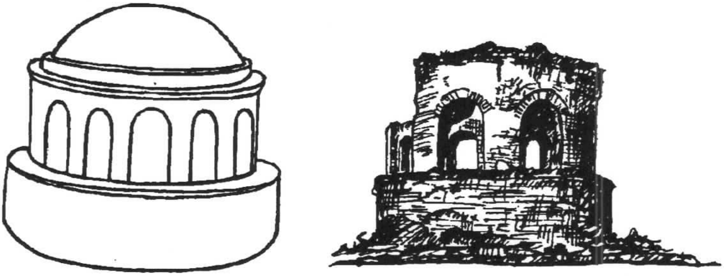


Fig. 55. Centric nature of the mausoleum of Helene

(Fig. 55), built in 330 A.D. near Rome. The deep niches of the top barrel are spanned by arches to allow the mass and rigidity to be uniformly shared by the mausoleum. Another disadvantage of the domes is that they are too rigid and heavy, in particular, when they are built in compliance with the Roman technology of cast concrete, for which reason ancient craftsmen always attempted to make the domes lighter and ductile, matching them with skeleton systems. In the above mausoleum of Helene, hollow ceramic amphoras were embedded in the dome to reduce weight. To decrease the dome weight, there existed domes that were made completely of hollow ceramic vessels inserted into each other, laid in a spiral-like manner and embedded in concrete.

It would be unjust to speak of the dome merely as a structure used for roofing buildings in order to protect them against the elements. At all times, and in all religions, including fire-worshippers, heathens, Christians, Mussulmen, the dome always looked the incarnation of Heaven, the home of Gods and saints. It was always associated with miracle creating the mood, so that lofty thoughts of religious persons were directed to it. Because of this, in constructing domes, ancient architects paid much attention to them. On the one hand, the domes ought to be perfect in construction to withstand any shaking loads, and, on the other, they must evoke high feelings. There follow specific examples of Roman domes. Let us start with Pantheon, an example of unique design and perfect embodiment of the construction technology of that time. Analysing this temple from the viewpoint of seismic

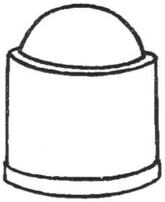


Fig. 56. Geometrical form of Pantheon resulted from conjugation of hemisphere and cylinder

stability, we see that Pantheon satisfies nearly all the above principles of earthquake-proof construction. Pantheon is, undoubtedly, a sample, or, to be more exact, an ideal of seismic stability, which has been proved by its survival for almost 2000 years. Though Pantheon underwent many underground storms, its walls show minute cracks not dangerous to the total integrity. Let us consider everything in succession.

Pantheon (temple of gods) was built in 118-128 A.D. during the reign of Hadrian. It is a very simple round temple (Fig. 56) that consists of a low-built barrel, 43.5 m in the inside diameter, vaulted by a spherical dome, 43.2 m in diameter, the total height being 43.0 m. The thickness of the cast concrete wall with brick facing is 6.7 m (Fig. 57). The thickness of the dome envelope varies from 1.80 m at the base to 1.20 m at the top (Fig. 58).

The barrel of the Pantheon walls is borne by a circular foundation, 7.3 m wide and 4.5 m deep. I have not found the description of the foundation structure in the publications of neither ancient, nor contemporary authors. Neither can I check it, but, undoubtedly, the foundation is a sandwich type, like that of Colosseum, ensuring seismic insulation with sliding of one course over another due to a sand layer. Moreover, earthquake waves are well dampened by a foundation of variable rigidity.

The above said indicates that from the standpoint of seismic stability, the general configuration of Pantheon is all-right. It is a purely centric building whose rigidities and masses are axisymmetrically distributed. Now we shall consider separate design elements of Pantheon but without going into detail.

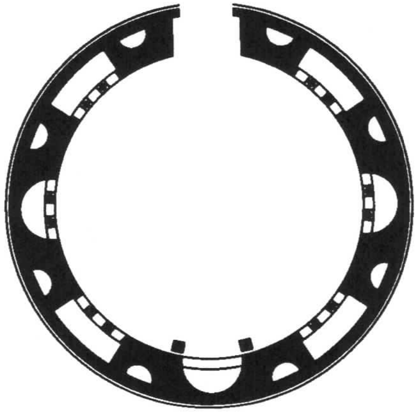


Fig. 57. Hollow of Pantheon wall

The walls of Pantheon were faced utilizing small bricks with large brick slabs placed at 1.0 m intervals that reliably tied the facing with the wall monolith. To take up the thrust produced by the dome, which was the largest in the world for about 2000 years and very heavy (one square meter of domed roofing weighed 7.3 tons), the walls were rather thick, 6.7 m, as was already said. However, to lighten the walls with a view to saving the materials and reducing their weight without affecting the strength and stability, eight niches were made, 8.9 m wide and 4.5 m deep, in the walls (Fig. 57). There were also smaller niches. This reduced the weight of the walls by one third. Therefore, the base part of the Pantheon walls formed eight interconnected masonry piers. The piers themselves had hollows to reduce weight. The upper part of the wall is more complicated in construction. Here the wall barrel was joined to the dome where builders were successful to unite the masses of both through a smoothly cast joint. Strong semicircular brick arches of double curvature running through the entire thickness of the wall were laid in the body of the upper wall. These arches overlapped the niches of the lower part of the wall and worked like elastic wavy springs that bore the dome with its double skeleton also made of bricks (Fig. 59). The work of double-curvature support arches is of interest. These arches went beyond

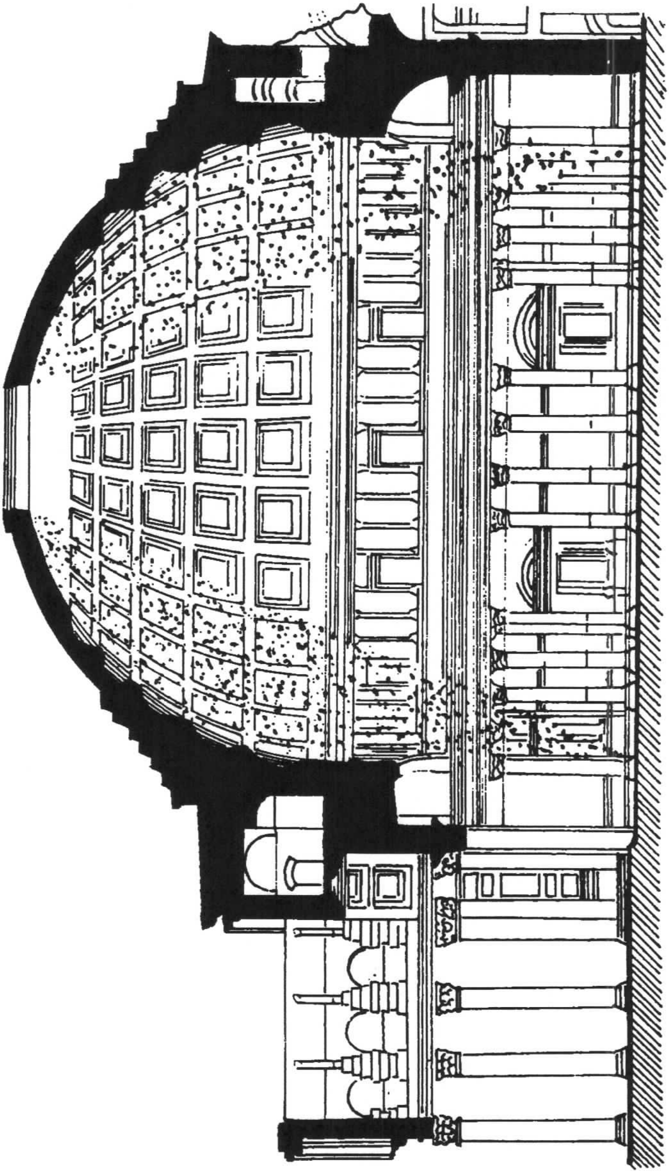


Fig. 58. Section view of Pantheon

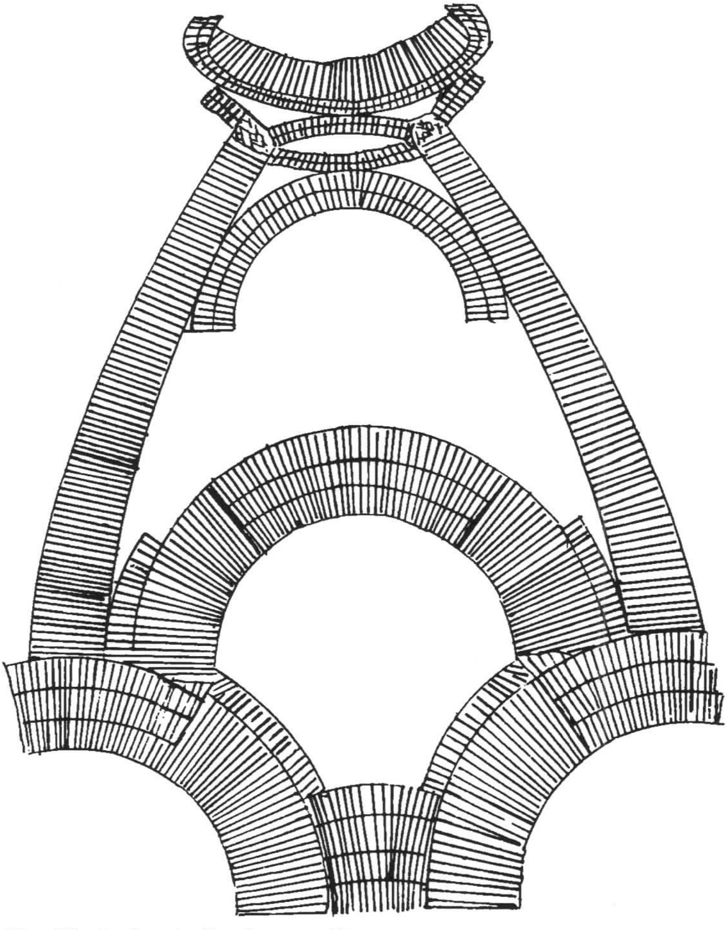


Fig. 59. Arches in Pantheon wall

their plane and, therefore, in addition to the compression, they underwent torsion caused by the above-lying load. The semicircular arch poorly stands to torsion loads developing extra stresses. However, the ancient builder managed to overcome this difficulty.

The cast dome of Pantheon has a very interesting structure. To provide elasticity, uniformity of strength properties, and equal settlements in concreting, two skeleton tied systems of bricks are

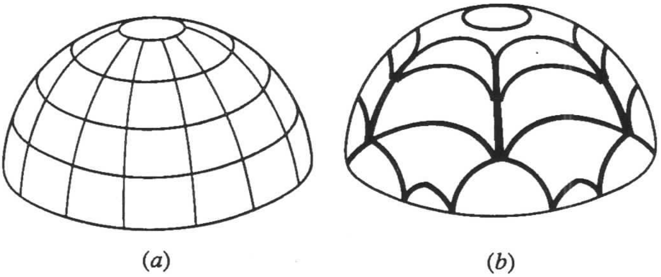


Fig. 60. Brick skeletons of Pantheon dome:
(*a*) internal; (*b*) external

embedded in the concrete body of the spherical dome (Fig. 60). The internal skeleton system consists of 5 lateral ribs and 28 meridional ribs. Of course, the whole system is closed to form a conventional skeleton. The other skeleton system is situated in the body of the dome monolith, above the former system. This system consists of eight stronger meridional ribs in accordance with the number of the wall piers and arches connecting these ribs into a unit skeleton. The ribs of the latter skeleton rest on the ductile arches spanning the wall piers, rather than on the rigid piers. Being embedded in the softer, somewhat ductile homogeneous body of the concrete dome, these two skeleton systems created a unique, as to the idea, dome resistant to earthquake effects. Many diverse domes reinforced by ribbed skeletons were created during the 2000 years that followed, but I never encountered double skeleton systems in the structures described.

Owing to the builders of genius, the glorious dome of Pantheon survives till now, and it is impossible to study its structure completely. Usually, only collapsed structures are well studied. There is something mysterious in this dome, which is difficult to understand from the standpoint of the contemporary concepts on the structure work. For example, a modern designer would align the meridional ribs of both skeleton systems without fail to make their tying easy. The ancient engineer would construct these ribs so that they could not match, using 8 and 28 ribs, when the ribs are not aligned anywhere in one vertical plane, though it is clear that they work together. Why is it done so? Maybe, this arrangement of ribs makes the dome more elastic or helps it to demonstrate ductility. All this needs to be studied. To my mind, nobody has seriously studied the construction of Pantheon from the viewpoint of its seismic stability, though this is a ready solution to many problems related to the earthquake-proof construction.

As was said above, Roman builders did their best to essentially reduce the weight of the walls of Pantheon, the more so they tried to lighten the dome. This was obviously done for the reasons of economy and aesthetics and, certainly, to improve the seismic stability of the building. The following two measures were taken to reduce the dome's weight. First, coffers were made along the entire bottom surface of the dome, i.e. depressions between the ribs of the lower rectangular skeleton. These coffers—voids—had fairly large size: 0.8 m deep at the dome base with 4.0 m in width. They were 0.6 m deep and 2.5 m wide at the top. There were 140 such cells in the dome. This reduced the dome weight essentially. By the way, the coffers were cast concurrently with the dome. The result was that the spherical envelope rested on an arched system formed by the ribs. Second, to reduce the weight of the dome, hard travertine stone was used as the aggregate of the concrete at the lower part of the dome, where the stresses were greatest. Lighter filling materials of tuff and pumice were utilized higher.

Huge stretching forces are present in the support ring of the vast dome of Pantheon. To take up these forces, the dome base concentrates huge masses of concrete and bricks, i.e. materials that badly work in tension.

Even this brief description of a remarkable Roman building demonstrates how well thought out were the temples constructed by ancient builders to make them stand forever.

Note that doubt was expressed about the existence of brick skeleton running through the entire height of the dome of Pantheon. It was supposed that the skeleton runs through only the height of two coffers. However, the Moscow International Congress on Shells, 1985, again considered the skeleton system of the entire dome. To my mind, the advocates of full skeletons are right. It is unlikely that Roman builders could leave a large bulk of concrete not reinforced with brick due to, say, the necessity of obtaining uniform settlement. Moreover, there ought to be something to mount and secure the scaffolds and centering in the course of concreting the upper dome's part.

The author of Pantheon was Appollodorus of Damascus, an outstanding architect, who took the liberty of making jokes about the architectural projects carried out personally by Roman emperor Hadrian and who was put to death for this by the emperor.

In order to compare different structures, let us consider another dome, of about the same dimensions and erected at the same place, but 14 centuries later. In the course of construction this dome saw a few authors, which allows us to trace their creative search in evolution.

From 1506 to 1546 the greatest architects (Bramante, Raphael, Peruzzi, Sangallo) tried to solve the most difficult architectural and design problems that arose in constructing St. Peter's basilica in Rome. Though, to be precise, the jobs to reconstruct St. Peter's basilica into a cathedral were commenced as far back as 1470.

The basilica is a girder-pillar structure consisting of a few, usually three, elongated longitudinal halls, naves, separated by rows of columns. In erecting the new temple, a more intricate architectural task was set. In addition to the large horizontal internal space, clerestory ought to be added, which could be done by introducing the underdome space. In this case, however, the dome had to rest on four pillars, rather than on bulky walls, as was the case with Pantheon. The pillars ought not to break the central space under the dome and the spaces of the side naves. Besides, the dome ought to soar highly above the cathedral, being raised by a barrel drum pierced with lighting openings. As you see, the structure became very complicated. In this event, the dome and the walls could not represent a monolithic unit, as was in Pantheon. Again, the building centre of gravity was raised on account of the highly raised dome. This affected the seismic stability of the building, as it disagreed with the principles of the earthquake-proof construction. To my mind, this was understood by those remarkable architects who built the cathedral. The further events took place as follows.

On instructions from Pope Julius II, Bramante, Donato d'Angelo (1444-1514), designed new St. Peter's cathedral (construction began in 1506). The total area of the building would be 134 by 134 m. According to the data available, the dome planned by Bramante was a copy of that of Pantheon with exactly the same internal diameter, 42.3 m. But usually there is no point in exactly copying under changed conditions. Like in the case with Pantheon, the new semispherical dome was supposed to be concealed under seven steps of the monolithic concrete with coffers made on the inside (Fig. 61*a*). Such a monolithic dome would obviously be very heavy. In Pantheon it was embedded in the concrete of the wall, while in the cathedral of Bramante it was raised by 48 columns laid out along the perimeter of the dome in three rows. A dome secured in this way could not stand even to wind loads, let alone earthquake loads. There were other design mistakes in Bramante's project of the cathedral. For example, four dome-bearing pillars whose erection started in his time were weak, and subsequent builders had to reinforce them. It follows from what was said that the first design of St. Peter's cathedral could not secure the seismic stability of that structure under the conditions of frequent earthquakes in the city of Rome.

After Bramante, the chief architect of the cathedral was appointed in the person of Raphael with his assistants Antonio Sangallo and Peruzzi. Unfortunately, because of wars and other political events, the construction work at the cathedral was practically not conducted from the death of Bramante in 1514 to the death of Peruzzi in 1536 who was appointed the chief architect of the cathedral in 1520 in place of Raphael. Here our attention must be drawn to the creative activities of Peruzzi who developed the centric plans generally and of St. Peter's cathedral, in particular. He sought a new design of the dome. Being aware, perhaps, of the disadvantages of the dome-bearing pillars of Bramante, Peruzzi reasonably suggested eight pillars in place of four, reinforcing them with 16 attached columns. As to the dome size, the proposals of Peruzzi were fantastic. He suggested to erect a dome 66.0 m in diameter in place of the dome 42.5 m in diameter. Next, he proposed to construct an enormous centric structure with a dome 185.0 m in diameter. That was really too much for a structure of stone, bricks and concrete, the more so in a highly seismic area.

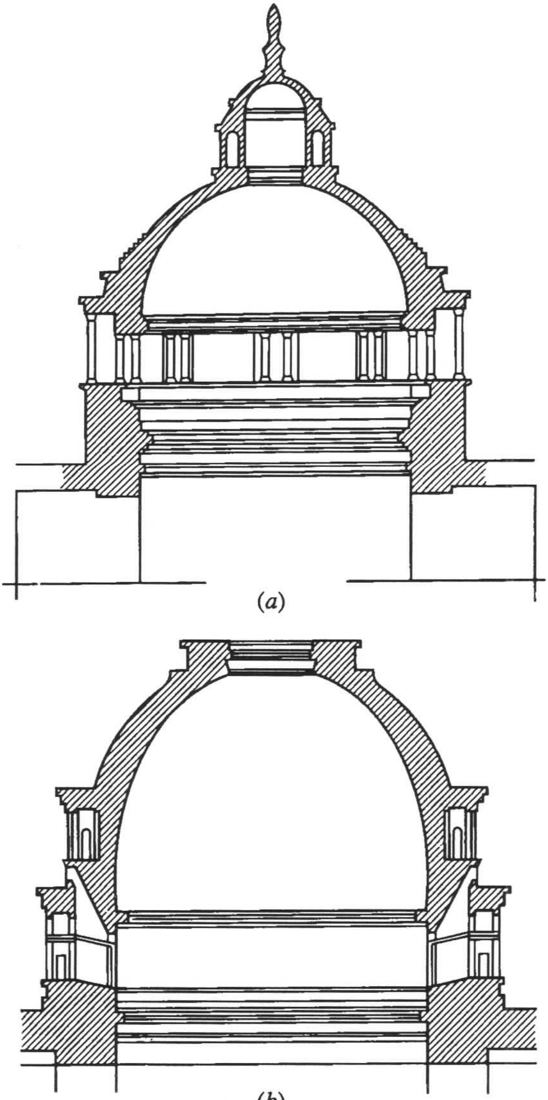
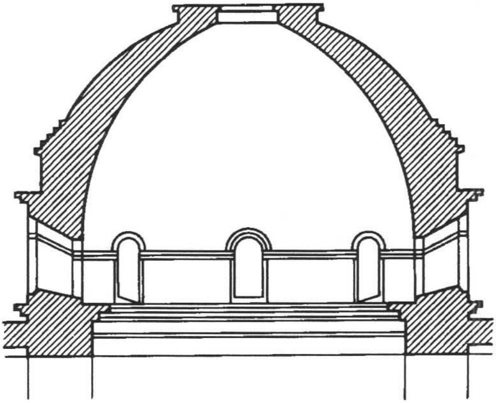
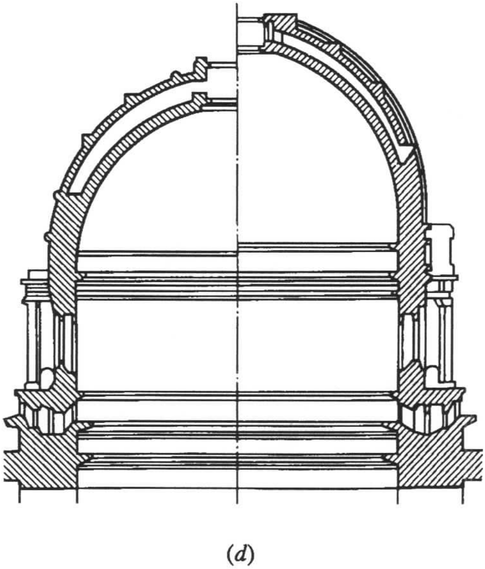


Fig. 61. Dome versions of St. Peter's cathedral:
(*a*) Bramante; (*b*) initial version of Sangallo;



(*c*)



(*d*)

Fig. 61. Dome versions of St. Peter's cathedral:
(*c*) last version of Sangallo; (*d*) Michelangelo

The construction of the cathedral was resumed in 1534 under Antonio Sangallo, and this stage of construction continued to 1546. The architect did his best to save all done by Bramante. We shall continue the discussion of the dome structure without considering the changes made in the building itself. We take most interest in how the dome structure was improved. The impression is that the architects were more interested in the dome's seismic stability than in architectural beauties.

In designing his first project of the dome, Sangallo tried to save only the external shape of Bramante's spherical dome and to make such structural changes that would correct the mistakes made by Bramante. First of all, he reinforced the joint between the dome and the barrel drum bearing it. To better take up the thrust caused by the dome, the drum wall was essentially thickened, from 4 m, as was in the structure of Bramante, to 7.5 m. Forty eight circular columns were left, but in the new project they were attached to a wall pierced by small window openings. This provided good joint between the dome and the bearing drum. The proposals to change the dome itself were interesting and advanced. With unchanged external spherical surface of the dome, the internal surface had the elevated shape that was introduced in Europe 100 years ago by Brunelleschi in the dome of the Florentine cathedral. The curve of Sangallo is pointed and is described from two centers to ensure smooth conjugation between the dome and the barrel (Fig. 61*b*). As was said, points (lancets) of domes and arches add to the seismic stability.

Evidently, the improvements made in the dome of Bramante did not satisfy Sangallo whose attention had been drawn by the idea of the lancet-like structures, and he began to bring it to perfection. The number of intermediate versions of the dome is unknown, except for the last version. The last project of St. Peter's cathedral was worked out in 1533 and is preserved till now in the form of a good model. In this project he, probably, synthesized the ideas of all previous versions and obtained the following results (Fig. 61*c*). In the last version, use was made of two interesting points. The dome's shape differed from all previous projects, being ellipsoidal, and elongated upward. This at once reduced the thrust caused by the dome and provided smooth conjugation between the dome and the drum. Another specific feature of Sangallo's dome that made it more stable is that its bottom part was embraced in a belt-like manner by two tiers of arcades. These arcades rested on the thickened wall of the drum that now reliably took up the thrust provoked by the dome. The underdome pillars were reinforced providing sufficient strength of the new version. However, very sharp dome hardened by two tiers of arches lost its proportions and architectural expressiveness. This project was not used.

In 1547 came the time of Michelangelo Buonarroti. Pope Paul III furnished him with wide powers by appointing him the chief architect of the cathedral, a commissioner, and an inspector. He charged Michelangelo with final completion of the cathedral, after putting in order the chaos that reigned in the construction site following the time of Bramante. Michelangelo subjected all done before to criticism and started the redesign work, using the experience already gained. He even tried to realize the dream of Bramante and to raise highly the spherical antique dome on a drum. As a result of an engineering analysis, this version was also rejected, and he started searching for his own solution. Note that all changes Michelangelo flatly made in the structure of the cathedral were aimed, on the one hand, at imparting monumentality and architectural wholeness to the building and at improving its seismic stability, on the other. Michelangelo suggested to do the alterations with a view to improving the seismic stability of the cathedral: he made its plan simpler, removed the projecting parts, and eliminated the corner towers. Most importance was attached to the central-dome space around which the symmetric building was formed with smoothly outlined conjugated walls free from sharp turns.

Certainly, Michelangelo paid particular attention to the dome as the most complicated and liable to earthquake damage element of the building. He made a few models of clay and wood. Already in the first model he utilized the double-dome structure (Fig. 61*d*) consisting of two shells connected by rigidity ribs. The material in such a double dome was distributed much better than in a solid dome, and the resultant dome became lighter. By the way, though the above-mentioned Florentine cathedral had two shells, only one of them was load-carrying, while the other shell performed the protective function. But Michelangelo made both shells load-carrying.

Michelangelo had time to erect the dome drum. The dome itself was completed in 1588-1590 by Jackome del la Porta who followed the ideas of Michelangelo and raised the dome by more than 4.0 m, thus reducing the thrust still more.

The structures created according to the ideas of Michelangelo feature elegance and delicacy, which is not always useful for the building from the viewpoint of durability. The wall of the drum erected by Michelangelo himself was 3.0 m thick. Sixteen counterforts were attached to the wall and three circular iron collars placed at the dome's base. However, all this turned out to be insufficient to withstand the thrust of an enormous dome more than 40 m in diameter. The stone counterforts separated from the brick wall of the drum, and to reinforce the dome in the 18th century, use was made of six collars, four for the dome and two for the drum. With respect to the strength, the bulky drum of Sangallo possessed certain advantages. It turned out that combining the principles of structural mechanics and architectural requirements proved difficult in such an enormous building as St. Peter's cathedral. As to the principles of seismic stability, they are met by the cathedral building itself. I do not know on what grounds and how the foundations have been laid, but the two-axisymmetrical structure satisfies the skeleton principle which implies that all load-bearing elements of the building, such as walls, pillars, columns, are interconnected to form united closed contours to guard against overloads of some elements in an earthquake. The 400 years' existence of the building proved its seismic stability.

Many domes have been considered by us in order to understand better what affects and what improves their seismic stability. This will be of use later, and we shall see how much common there is in the human mentality, though as dictated by the local traditions and construction materials, the structural realization may differ, the ideas being similar. There are some more short dome stories.

The Roman builders paid much attention to the lightening of different structures, domes in particular. It is known that empty

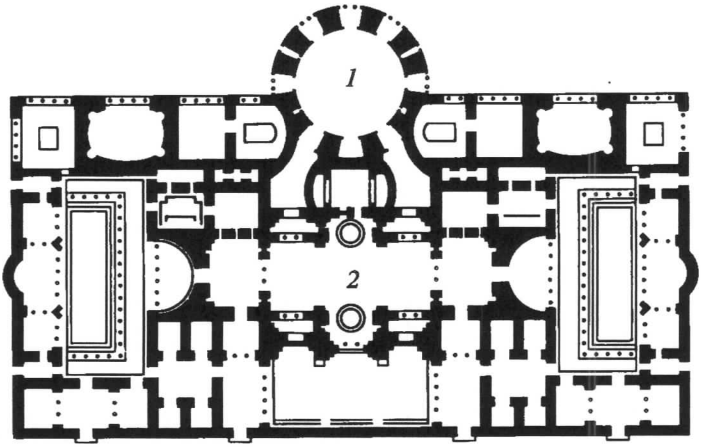


Fig. 62. Symmetric irregularity of the therms of Caracalla

clay amphoras and pumice were embedded in the body of dome of Pantheon. Sometimes embedded in the body of a dome were rings assembled of clay hollow vessels inserted into each other. There are still more unique Roman structures whose construction technology deserves our admiration. However, the objective of this publication is not to study the whole of the Roman architecture. Our task is much more modest. We are interested only in antiearthquake methods that can be demonstrated only on a limited number of examples. Therefore, we shall not continue the analysis of a large number of mausoleums, aqueducts, bridges, villas, basilicas. It seems to me that all said witnessed the high professional skill of Roman builders, good organization of the jobs they carried out, high workmanship of their structures, and also the fact that they paid attention to the seismic stability.

Before parting with the Roman age, let us consider several examples.

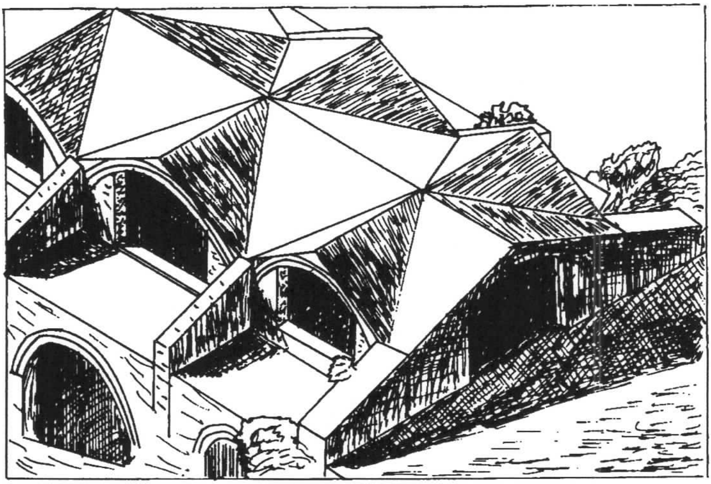
At the beginning of the 3rd century (212-216), colossal multi-purpose public structures, therms of Caracalla, were built under emperors of the Severus dynasty in Rome. The main building was 214 by 110 m in size (Fig. 62) and consisted of symmetrically laid out rooms of different height and area spanned by different structural elements. In short, this building, though having one plane of symmetry, was very nonuniform and irregular in structure. Generally speaking, this violates the principles of earthquake-proof construction, which reject such construction techniques. To see the results of this violation, we have to consider the therm structure in detail.

Referring to the plan of the therms, the structure was concentrated around and adjacent to the round hall with pools, which was roofed, like Pantheon, by a cast dome 35 m in diameter (*1*). The central place in the therms was occupied by a large hall, 20.0 by 54.0 m in size, roofed by three cross-barrel vaults of cast concrete that rested on eight poles with attached columns (*2*). Those were the two highest parts of the therms. They were surrounded by numerous lower vaulted rooms which took up the thrust caused by the above parts. Note that by the transmitted and accepted thrust forces the building parts were connected, supporting each another. There were no antiearthquake joints that would divide this enormous building into separate parts which could independently deform in an earthquake. That was one more violation of the principles of earthquake-resistant construction. From the viewpoint of seismic stability, another disadvantage of the structure may include its location on a hill slope and, therefore, a nonuniform ground bedding. All the other elements, namely, the material of the structure and the strength of the load-carrying elements, met the seismic stability requirements. According to A.S. Bashkirov, there is a curious, even debatable reasoning on the seismic stability of the structures employed by the therms of Caracalla. He believed that the variety of structures helped ancient builders to substitute disharmonic chaotic for harmonic motions, thus dampening the building shaking caused by an earthquake. He evidently meant synchronous and asynchronous oscillations of the structure elements. Actually, nonuniformity of a structure may cause some damping of oscillations, but somewhere oscillation superimposition may occur, for which reason it is better to have uniform structures in highly seismic areas. In the latter case stresses will be uniformly shared, otherwise underloads and overloads will take place concurrently. However, the therms of Caracalla can be seen today in ruins mainly due to earthquake shocks and then owing to shady deeds of people.

Contrary to the therms of Caracalla that had only irregular general structure, the basilica of Constantine was an ideal regular edifice (Fig. 63). This basilica is one of the latest masterpieces of the Roman construction skill. It was constructed on the Roman forum in 307-312. The structural design of the central basilica nave is similar to that of the main hall of the therms of Caracalla, but the former is larger. The central nave is vaulted by three rectangular (in plan) cross vaults built by the Roman techniques of cast concrete and reinforced with brick ribs. The nave is 80 by 25 m in size (in plan) and 35 m high. The dimensions of the basilica itself (also in plan) are 100 by 75 m.

An impression is created (Fig. 63) that the Constantine basilica structure represents a well thought-out regular structure. Three cross vaults of the central nave form a single monolithic rigid disk that weighs, however, a bit too much—7000 tons. The resultant weight is due to the cross vaults that are thick concrete bodies, rather than simply thin shells. Underneath the cross vaults have the form of crossing cylindrical surfaces while their top surfaces form a gable roofing. The system of cross vaults is supported by thick poles retained in place, as is shown by the basilica plan, by transverse wall-counterforts. The same wall-counterforts, located in the side naves and tied to each other by barrel vaults, well take up the thrust produced by the cross vaults. All the vaults are reinforced by double brickwork arches, 1.20 by 0.60 m in cross-section, located above each other. The structure materials are good bricks and strong cast Roman concrete. The materials in the basilica retained high strength properties till our time. It would seem that the whole edifice built so wisely ought to survive. However, even this materpiece of the late Roman architecture had errors that led to its collapse during an earthquake.

The basic structural disadvantage of the basilica of Constantine consisted in its nonuniform base. Practically, a diagonal of the edifice was represented by a riffle of tuff rock on which the basilica directly stood. Sandwich concrete substructures were laid along another diagonal of the base. At one angle their thickness was 6.0-8.0 m and at the other angle, 5.0-6.0 m. Prior to the



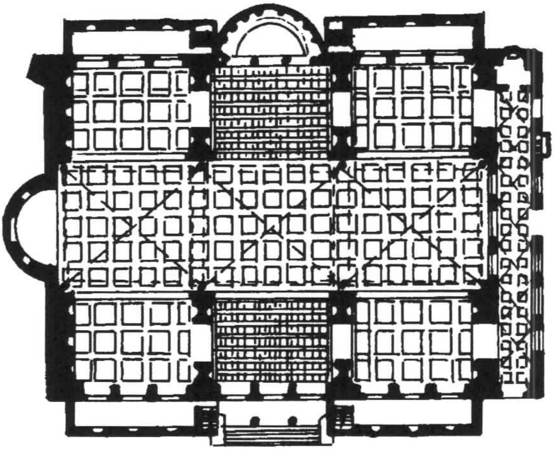


Fig. 63. Cross vaults of the basilica of Constantine

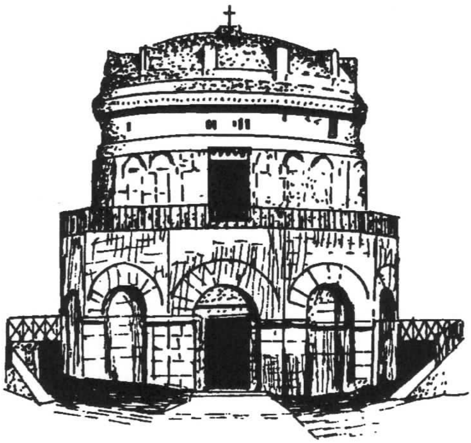


Fig. 64. Monolithic body of the tomb of Theodoric

foundation concreting, at least part of the rock had to be removed, but this was not done. As a result, the deformation properties of the edifice base differed, i.e. the rock was rigid, the sandwich foundations were ductile. Moreover, the heels of the cross vaults were shifted towards the centre of the nave and were only partially supported by the bulky poles. Naturally, nonuniform settlements of foundations occurred during an earthquake to break the cross vaults into two. In this case negative effects were also provoked by high weights and long vault spans.

Now goes the last example from the history of the Roman architecture. A unique case is known of making a monolithic multiton dome of one-piece stone. This is a dome above the tomb of Theodoric in Ravenna. Theodoric, the king of Ostrogoths, who well held out against the Byzantine Empire, died in 526. The dome was one-piece hewed in Istria and delivered by towing between two ships to a shallow place wherefrom it was hauled to the site of installation (Fig. 64). When I recall this event, some questions arise. What was this done for? Whether they wanted to create the 8th wonder of the world, or was it a principle of Roman builders to construct edifices as monolithic and uniform as possible? Maybe, the builders were made perform this unimaginable work by a caprice of the customer.

This completes our study of the seismic stability of Roman edifices [21, 22, 23]. I hope the lessons of ancient builders will be useful for contemporary builders. Let us follow the Roman emperor Constantine.

Brick and Stone of Byzantium

The crisis of the slave-holding economy in the western area of the Roman Empire brought about a new empire in the East—the Byzantine Empire with rudiments of feudal relations. This crisis eliminated compacted concrete from the arsenal of builders, which became less adequate in the new social and economic way of life. Besides, the puzzolana bed was now on the territory of the Ostrogoths to become unavailable for Byzantine builders. The following fact is curious. The walls of the city of Constantinople erected shortly after the city had been founded (330), using the Roman technique of cast concrete, surprised as a miracle already at the time of the emperor Justinian (527-565). The technique of cast concrete was so thoroughly forgotten that the citizens were astonished thinking that the walls had been chiselled of solid stone, although somewhat similar to cast concrete, cobblestone masonry, was utilized. The cobblestone masonry was done on a lime mortar by laying course of crushed stone and then a layer of mortar in the framework without compacting. This kind of masonry saved much manual labour as compared with the cast concrete technique. However, the strength of this masonry was much less which, naturally, limited the height of buildings where cobblestone masonry was employed.

Of the construction materials utilized by ancient Rome the Byzantine Empire inherited stone and brick. First, for construction of new buildings these materials were taken from old Roman structures. Then the production of bricks was organized in Byzantium. While Roman bricks were made of pure, well mixed clay subjected to intensive and uniform burning, which allowed the production of bricks 70 by 70 by 8 cm in size, Byzantine bricks were made of clay not so well mixed and with admixtures of stone, 35 by 35 by 5 cm in size. This, naturally, affected the brick quality. Altogether, the distinctive construction technology of Byzantium with many new elements was lower in quality than the Roman high-quality, exactly organized construction technology. Hence, the failures of Byzantine buildings during earthquakes were more frequent than those of Roman edifices. In Byzantium domes collapsed more often. Even such a unique edifice as Hagia Sophia in Constantinople is known for the dome collapse during earthquakes. Let us consider it in a regular manner.

In studying the seismic stability of Byzantine edifices, we shall follow the pattern used before. We shall not examine the construction methods of that time, nor analyse in detail the history of architecture. We shall separate and analyse the new features in the structure of Byzantine buildings from the viewpoint of resistance to earthquake shocks, preferably using, as an example, a building that survived, and consider some particular seismic stability elements of the structures related to that time.

It was said above that there might exist two construction systems, the girder-pillar and dome systems, the latter being usually centric. The third system—synthesized of the first two—developed in Byzantium. This was a product of the Christian age when large buildings crowned with domes symbolizing heaven were needed for divine services. The synthesized systems were large elongated buildings built as girder-pillar structures with a dome raised above their centre and borne by special piers or walls. Such structures appeared approximately in the 5th century to harmoniously combine the longitudinal and centric systems and traditions of the West and East. By the way, the origination of Christianity was marked by an earthquake. According to the Bible, the resurrection of Christ started with an earthquake that threw aside the stone slab covering the entrance to the cave where Christ had been buried. Only then the Angel descended, and the women came up. Christianity established new requirements to the construction of monumental religious structures. Earlier only the elite and priests were admitted to the temple, and all religious actions took place outdoors. Now the praying people gathered indoors, and this required room for all of them. At the same time, the temple interior ought to properly impress the praying people.

Studying the construction art of the Byzantine Empire, we shall, naturally, begin with the finest church Hagia Sophia in

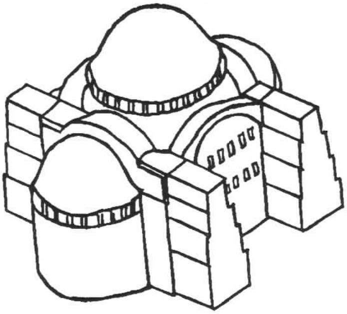


Fig. 65. Geometrical form of Hagia Sophia

Constantinople (532-537), which is a remarkable monument of the world architecture started by the emperor Justinian. The geometrical form of this church is fairly simple (Fig. 65) and consists of three architectural figures gradually developing one into another. These are a ground plan rectangle, an intermediate oval of the semidomes, and a circumference of the dome. All together form somewhat average between a longitudinal basilica and a centric building. The cathedral is vaulted by a large light dome 33 m in diameter. The dome is borne in an original manner. At two sides it rests on arches built of bricks taken from old Roman buildings. Adjoined to the arches are side semidomes that take up the longitudinal thrust produced by the main dome. On the other two sides the dome rests on the walls reinforced by arches and supported against the dome thrust by pillars-counterforts.

The principal construction material of Hagia Sophia is brick laid with mortar prepared of lime, crushed brick, sand and water. Courses of chiselled stone were laid in the masonry as antiseismic belts. The four underdome support poles were made of hard limestone blocks. To ensure the uniform load distribution in the masonry, lead plates were placed into seams between the stone blocks.

It is interesting that highly ductile lead plates, thus protecting the stone masonry against stress concentrations, served at the same time as insulators of oscillations propagating in this masonry. Byzantine architects widely used lead in their structures. For example, lead plates were placed on and under columns to provide uniform loading of the column and protect it against eccentric compression even in the case of unequal settlements of the whole structure. The lead was held by metallic hoops not to be squeezed out.

Hagia Sophia has survived till our days, and I hope it will stand many more years. However, it is deprived of simplicity and harmony an earthquake-proof building needs, which are observed in Pantheon.

Let us discuss certain disadvantages of Hagia Sophia that are not few in number.

First of all, the general configuration illustrated in our diagram shows four heavy counterforts weakly interconnected by arches. During an earthquake these counterforts would support, as it were, the whole cathedral and take up the dome thrust, on the one hand, and, on the other, they would oscillate independently, exerting extra loads on the cathedral walls and tending to separate. Moreover, the counterforts opposing each other did not have a common centre line and were displaced, and during an earthquake they would provoke twisting of the building. Next those pillars-counterforts were not strong enough. They had leaned over already during erecting the girth arches and parted by 65 cm upon completion of the construction work. Most likely, this happened owing to a nonuniform ground bedding. It comes out that some elements in the building failed before any earthquake, which is inadmissible for an earthquake-resistant building. In order to reinforce the weak ground base, a system of vaults supporting a homogeneous concrete slab had to be provided under the whole cathedral. It was this slab on which foundations of the edifice were laid. This vast vaulted underground structure, called a cistern, was very characteristic of Byzantine architecture. These cisterns served not only as substructures under the foundations of edifices, but could be used as various commercial rooms, including water storage. Later we shall consider an example of such a cistern.

Now we shall discuss the principal architectural and structural component of Hagia Sophia, i.e. its dome. The rise of the church initial dome was very small, about 8.2 m in total, which is one fourth of the dome diameter. The thrust of such a dome is great, which is inadmissible from the standpoint of seismic stability. Most likely, the architect Anthemius was aware of Syrian high-rise domes producing low thrust, but he was enthusiastic about the artistic conception. The result was the dome collapse during an earthquake on the 32nd year of Justinian reign.

The new dome of Isidore Junior (563) was erected in the form of a hemisphere and was 6.3 m higher than the old one. This is a lightened ribbed dome whose fourty ribs rest on the forty window piers that are 2.4 m thick and perform the function of counterforts. Next there are four girth arches bearing the dome, which differ in rigidity, as they are connected with different structures: two are tied to the hemispheres and the other two with the walls. Naturally, during an earthquake the supports of different rigidity cause unequal stresses in the dome. All this led to several failures of the dome which was recovered with improvements at the Byzantine time. An example is as follows. The collar beams of metal in the dome base had been used before for construction purposes and were cut off upon completion of the construction work. Now they were left because, as was observed, they took up some thrust, thereby adding to seismic stability of the dome. The dome was fixed by a metallic hoop when the cathedral was substantially restored in the 15th century, and many unsound columns had to be levelled.

All building structures may be divided into two large classes by their predisposition to deformation: flexible and rigid. By its structure and materials, Hagia Sophia (St. Sophia) refers to the class of rigid buildings. However, its rigidity is, probably, insufficient and its parts can move relative to each other breaking the ties. This accounts for the principal disadvantage of the cathedral structure.

Naturally, Byzantine architects continued their quest for new, more perfect structural schemes in compliance with the requirements for the synthesized systems mentioned above. Finally, such a structure was found in the form of a cross-vaulted architectural system known as the principal achievement of Byzantine craftsmen. Though this is a controversial question, since certain authors maintain that the cross-vaulted system was first used in Armenia. Perhaps, both are right. We, however, are most interested in the fact that these systems have been invented, rather than where they have appeared, and what their

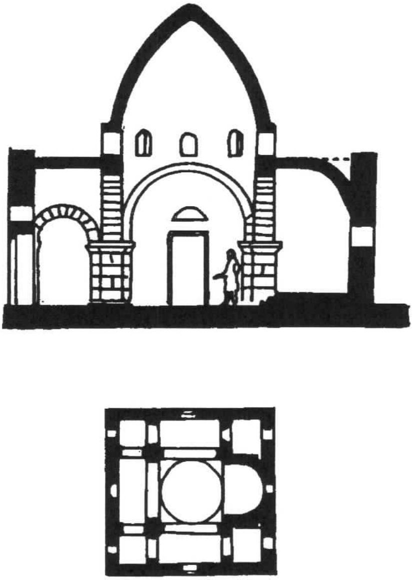


Fig. 66. Cross-vaulted system

advantages and disadvantages are to be taken into consideration when constructing in seismic regions.

Apart from the architectural-artistic and structural details typical for a specific building, the idea of a cross-vaulted system is as follows. It is an area square in plan, which is surrounded by four walls. There are four sufficiently strong supports that are symmetrically located in the centre of this square and bear the dome representing the artistic and structural centre of the construction. The central dome ceils the central cell of the building. The other eight cells formed by four central supports are commonly vaulted by barrel vaults. Note that primordially, from the standpoint of seismic stability, the structure is symmetrical with uniformly distributed masses. The only element that affects the general harmony is the central dome which is highly raised by a barrel or polygonal drum. Accordingly, it must be secured in place. Proceeding from the skeleton principle, the central supports must also be well connected to the walls. In short, the cross-

Fig. 67. Heavy-duty arch and reinforcing a stone wall with brick tiers

vaulted system meets in principle the seismic stability requirements. However, a final conclusion on seismic stability of a specific building can be made only after examining its structure in detail. The following example will be presented to consider a specific diagram of the cross-vaulted edifice.

It may be said that the classical ideal scheme of a cross-vaulted edifice is represented by the church in Ile-Anderin in Syria, the 6th century (Fig. 66). This figure shows that masses and rigidity in this structure are distributed uniformly and symmetrically with regard to the planes of symmetry. But the most important thing is that the dome is reliably supported vertically and horizontally. It is vertically supported by four strong pillars, while the rigidity of its embedment in the ceiling is ensured by the adjacent barrel vaults forming a firm cross. Besides, the cross-vaulted system meets one more principle of the earthquake-proof construction that was called above the skeleton principle implying that the vertical and horizontal contours of the structure are ensured to be closed. We shall not discuss in detail the structure shown in Fig. 66, as it will be dealt with in the next chapter when studying cross-vaulted systems of Armenia.

A feature of interest observed in the construction technology of the Byzantine Empire consists in laying the belts of stone in the brick masonry, as shown in Fig. 67. The same figure illustrates a wall fragment where one can see a heavy-duty arch spanning the

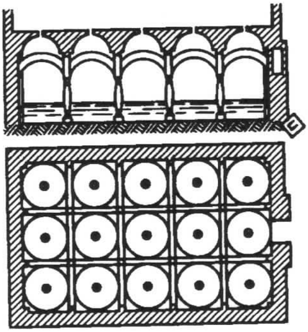


Fig. 68. Regular structure of cistern in Constantinople

gate. The arch was built of four tiers of flat-laid bricks. Sometimes, just the other way round, tiers of bricks were laid in the stone masonry. Use was also made of thick layers of mortar that were equal to the brick in thickness. All this was done to impart plasticity, elasticity and bonding to the masonry.

There existed one more type of outstanding structures in Constantinople and its neighbourhood. Some of them have survived and exist today, which points to their resistance to earthquakes. These are the so-called cisterns one of which was mentioned. It formed a vast stage that served as the base of Hagia Sophia. All cisterns are similar in construction and differ only in the floor area, always rectangular-formed, and in the number of floors, occasionally reaching 3. The vast compartments were ceiled with the aid of small-span vaults supported by many columns. In Constantinople there was an especially large structure, 72 by 65 m in plan area, called Bin-Bir-Direk, which meant one thousand and one columns (Fig. 68). The cisterns in question were typical structures. How skilled in brickwork the ancient craftsmen ought to be to lay multiple arches spanned from column to column in all directions, and to combine those arches into a vaulted whole unit for which the arches were used as the rigidity ribs. The firm disk of the vaulted ceiling was tied to the bulky rectangle of thick walls employed to hold the entire roofing (flooring) against horizontal displacement in case of an earthquake shock, since the columns practically take up only vertical loads. I could not find

Fig. 69. Bridge corbeled system

the description of the foundations for this structure anywhere. From the viewpoint of seismic stability, we shall treat this important factor as the unknown.

Now we shall consider one more interesting design method known in Byzantium. Figure 67 shows a conventional arched ceiling, like that which could be built by the Romans. However, sometimes the Byzantines made use of different structure vaults that could never be used by the Romans. In construction of long structures, like aqueducts and bridges, Roman builders arched the spans between the supports. The thrust thus caused by semicircular arches was counterbalanced through the supports by the thrust produced by neighbouring arches. The result was that failure of any support or arch might cause a chain collapse of the neighbouring arches that would thus be in an unbalanced state. This situation could not take place in certain Byzantine structures of this type, since they had quite another design where each semiarch was as if a console of variable rigidity, while the arch itself was split in the arch key plane. The result was that semiarches were merely in contact in the split joint without mutual loading. Each support carrying a pair of semiarches-consoles is a balanced system, and the failure of a span does not affect the strength of the structure. By the way, this structure is utilized up till now to construct bridges in mountainous areas in the East, say, in India, the Caucasus, and Dagestan. If that is the case, bank and intermediate abutments are made in the form of beams varying in cross-section (Fig. 69) that are connected by a shortened decking of the bridge to essentially reduce the span bending moment. The

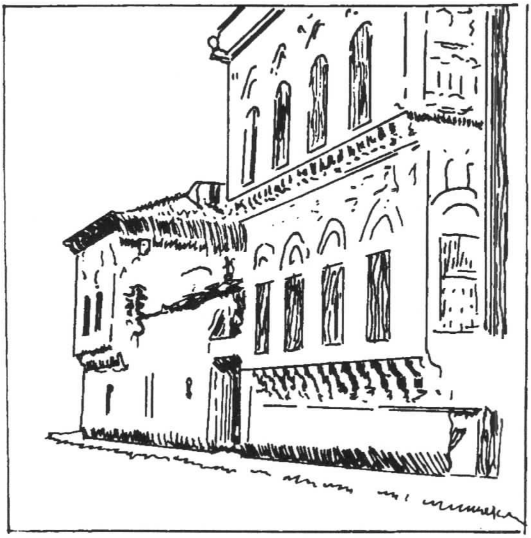


Fig. 70. Stepped walls of dwelling houses in Byzantium

resultant structure of such a bridge is resistant to earthquake effects. Independent displacements of the flexibly coupled abutments are not dangerous for the bridge structure.

One more unsuccessful method of construction, which became traditional in the house building of Constantinople, is worth mentioning. In the 6th century, the East traditions began to get widely into Byzantium. At the same time, the city began lacking ground areas for building. It was then that a tradition developed to build balconies and extend the first storeys towards the street (Fig. 70). The walls of the ground storeys were thus off-centre loaded. The result was that none of such houses survived to be destroyed mainly by earthquakes [24, 25, 26].

From the Byzantine Empire our way runs further eastward, to those states that were in close contact with the empire, i.e. to Armenia and Georgia.

The Caucasus
From The Black Sea
To The Caspian Sea

Seismic Stability of Armenian and Georgian Temples

Now we are in the Caucasus, the area in which the traces of all past civilizations can be found, where states with distinctive culture and vast international relations existed long since. I invite you to start our trip over the Caucasus with Armenia. We shall consider structures built in this area during the New Age, i.e. after Christmas.

Let us consider the most wonderful edifice of the 1st century, the ancient temple of Garni, which had a miraculous escape of destruction after the adoption of Christianity in Armenia by Tradat III, at the very beginning of the 4th century. This temple is not an exception, to my mind, at that time there existed many of such temples. But after Christianity was adopted in Armenia as a state religion, the heathen structures were destroyed and replaced by crosses. Later Christian temples were erected in those sites. Thus, the outstanding monument of the Armenian architecture, the Echmiadzin cathedral, was built in the site of a cross erected in memory of Gregory the Enlightener, the cross, in turn, being placed on the site of a destroyed heathen temple.

We shall not analyse all other ancient edifices of the citadel of Garni which is situated only at a distance of 27 km from the city of Yerevan, although we could find much of interest amid the remnants of defensive works, public baths, and temples. One can see something from the time of the early Bronze Age, i.e. the remnants of structures related to millennium III B.C. To my mind, it will be enough to consider solely the Garni temple in order to form a true notion of unfeasibly high construction technology used at that time and highly skilled consideration of its antiearthquake measures.

At first sight you are somewhat bewildered by the ancient temple of Garni. You are facing as if a true Greek peripter with volutes of Ionic order columns (Fig. 71). But this is only at first sight. Actually, it harmoniously combines Greek forms and construction techniques of the mastery of Armenian builders. The Armenians have built their temple of basalt-cut structural members. Greek craftsmen worked with marble and limestone and could not work out hard basaltic rock. Like in all other cases, we shall start with the foundation.

The temple stands not far from a precipice brink, on an inclined rock that has been levelled with the aid of rubble concrete and sand to obtain a horizontal stage. The thickness of a rubble-concrete course nearer the precipice is up to 2.5-3.0 m, tapering away to nothing at the opposite side. The supporting stage, the so-called podium of the temple, is laid in the East manner and made of the same rubble-concrete. The walls are dry-laid, without mortar, as it should be in a Greek temple. Stones in the walls are horizontally and vertically interconnected with iron dowels and brackets sealed with lead, the walls being laid of single stones so that the wall width equals the stone width. Note, the column parts are connected to each other, the floor plate and the ceiling by two and three bronze rods, while the Greeks in such cases employed one central dowel. The ceiling parts are also interconnected by rods and brackets. There is convincing evidence that the Garni temple had above cella, its central part, the ceiling in the form of a barrel vault, 5.5 m span, of key stones laid on a lime mortar concurrently with metallic ties. We have encountered this structure of vaults in the Black sea coastal Greek settlements. As you remember, the Greeks did not use vaults in ceilings of their temples. They made light wooden rufter-type roofings. This temple was built completely of stone. The space between the cella domes and the flat ceiling comprising slabs above the side colonnades and the roof had been filled with lime mortar

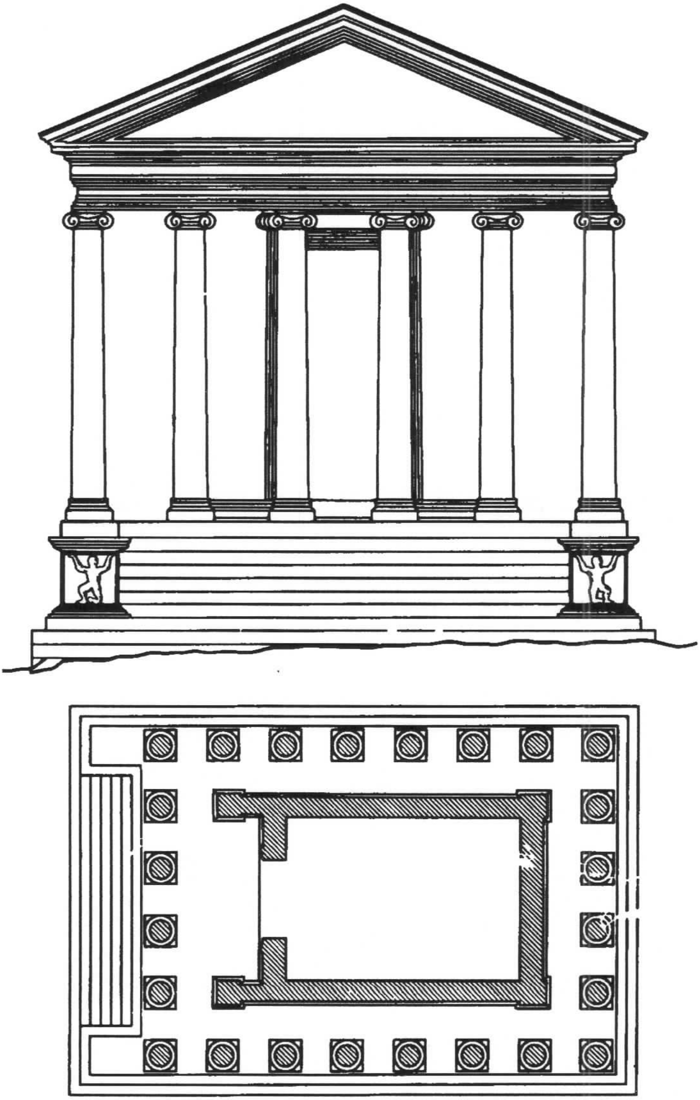


Fig. 71. Garni temple—Greek form and Armenian construction techniques

containing light aggregate of volcanic stones. Therefore, the gable surface of the roof was formed by rubble concrete fully filling the space between the ceiling and the tile roof. We encountered this design of ceiling made of bulky cast concrete in the basilica of Constantine that was built more than 200 years after the temple of Garni.

An analysis of the structural diagram of the temple described will give us a design model of an edifice not yet encountered anywhere. We have considered till now ductile schemes of the Greek temple type, or rigid monoliths of Roman edifices. Now we face as if a combined scheme which looks as follows. Two utter rigid slabs, the lower being a stage (platform) of heavy rubble concrete and the upper—a ceiling of stone and light rubble concrete, and between them a ductile supporting connection comprising the columns and walls, which is formed by dry-laid stone blocks interconnected by elastoplastic ties. In this model of structure all masses and rigidity are symmetrical with regard to the longitudinal plane of symmetry. The plan dimensions of the structure are moderate, of the order of 11 by 15 m to meet the seismic stability requirements. Given the described structural scheme of the edifice, the ductile columns and walls perform the function of seismic insulators during an earthquake. The shaking of the lower rigid slab is not fully transmitted to the upper plate owing to the dampening action of ductile walls and columns. Accordingly, the earthquake loads are reduced in such a building. As you see, the structural scheme of this edifice is quite definite, the rigid type of a foundation supporting slab corresponds to a rigid nondeforming ceiling.

In short, a whole set of earthquake-proof measures, such as seismic insulation, symmetry, weight reduction due to the use of light aggregates in the concrete, elastoplastic tie between the elements, strength, corbeled systems, all these together helped the temple resist earthquake shocks during sixteen centuries. The temple collapsed in 1679 during an earthquake, since after the fire arms invention local inhabitants managed to get lead from the joint ties, which badly affected its earthquake resistance. But for this, the temple might survive till our time. Perhaps, the major disadvantage of this temple from the seismic-stability standpoint was a heavy roofing inherited from Greek traditions. Not long ago, the temple has been restored so that it can stand to earthquake intensity nine.

We analysed an outstanding structure built by Armenian architects in ancient times and saw the high standards and first-rate workmanship of construction techniques that existed two millennia ago. Now it is time to see what the matter was with the earthquake-resistant construction at the time of early Middle Ages. An example might be the world-known cathedral, the still existing Echmiadzin temple, the 3rd-4th century, but I think it's much better to consider a more centric church of Bagaran which is also related to the cross-vaulted structures. To my mind, it is correct to say "centric", we may even use a measure of centric state. This church does not exist now, though at the beginning of this century it was in a good condition, only the dome failed. Being on the Armenian territory that passed to Turkey in 1920, the church was completely demolished in the middle of this century.

The church of Bagaran was built in 624-631. Figure 72 shows its centric plan and a general view of a three-storey centric edifice. Let us start the study of this church with its plan. The plan diagram demonstrates that the church has two planes of symmetry. This ensures the uniform distribution of the rigidity and masses of the church. Note that four pillars supporting the dome are widely placed and approach the walls. This is done to increase the space under the dome. However, certain structural problems arise in connection with this. The large spacing arches spanning these pillars and supporting the drum of a rather heavy dome produce much thrust too. To take it up, the pillars are connected to the walls whose stability, in turn, is provided by protruding pentahedron counterforts. It is this sequence of interconnected elements that provides the strength, rigidity, and joint work of the vaulted ceilings of the ground and first storeys. This is what an earthquake-proof building needs.

Figure 72 shows how the cross of barrel shells covered by gable roof is raised to the first storey. This cross is conjugated to the dome through the underdome drum. This system allows the dome structure to be reliably supported by the pillars and walls of the church. The church structure is a single rigid system. The

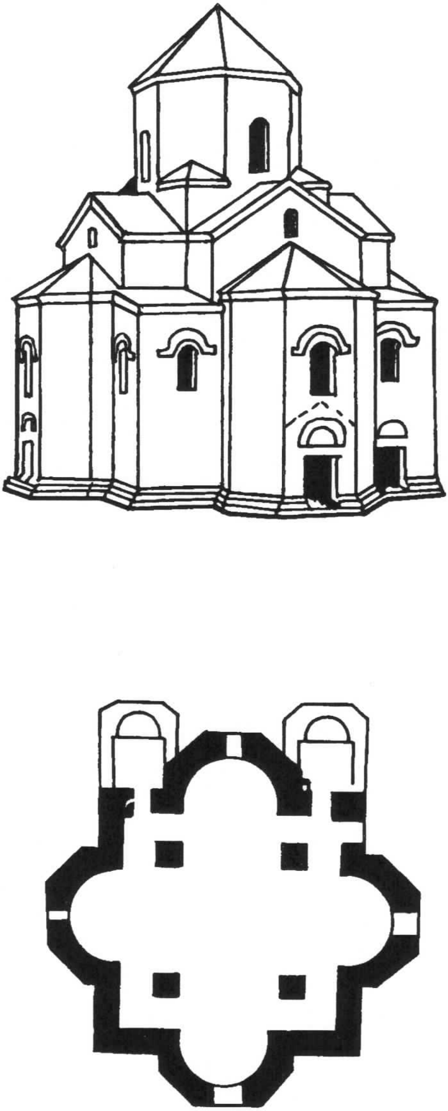


Fig. 72. Centric nature of the cross-vaulted system of the Bagaran church, general view, plan

earthquake resistance of the building is dependent upon the strength of its walls, floorings and ceilings, for which reason let us have a more detailed talk about the design of walls and domes that were generally used in Armenia, in addition to the church examined.

Stone is the principal construction material that was available for Armenian architects. Times and people changed, and the techniques of laying stone walls changed too. Unfortunately, those changes were not always positive, as we would like to. Studying the ancient temple of Garni, we saw that in the 1st century dry masonry was laid of large stones cut-fitted to each other and interconnected by iron and bronze dowels and brackets sealed with lead. And it was only 2000 years ago! And what was the masonry used before? At the pre-Christian times the masonry was laid of huge stones of different size, well fitted to each other. This masonry was called cyclopean. Imagine how much mastery and handicraft, and mainly diligence and workmanship, were required to cut, chisel, move, and fit in place the multiton stones of basalt.

In the first church edifices three-course nonuniform masonry was utilized consisting of two parallel courses of stones with the space between them filled by lime mortar and stones. Nobody used solid dry-laid masonry of stone blocks fitted to one another. The inner fill of concrete in the first buildings was insignificant, accordingly, the whole load was taken up by the stone. This design of walls could not, probably, provide the required strength, since all inner voids were difficult to be filled with concrete, and, hence, the two courses of stones would be poorly bonded and might not work together. Then more perfect walls were constructed. The stone was now used for facing only, and during the construction work also as the casing filled with coarse flat rubble poured over with lime mortar.

The facing plates were chiselled and fitted in place so accurately that no mortar solution was squeezed out. With this design of walls, the load was taken up by the concrete core and, even if the facing fell off, the walls remained capable of load carrying. The seismic stability of such monolithic walls limited by facing plates on both sides had been proved by many severe shocks of earthquakes to which the ancient buildings of Armenia were subjected for many centuries. These buildings, as a rule, survived, and if not, they collapsed saving large fragments intact.

Further improvements were as follows. Stone, lime, and labour were saved still more, and, therefore, the walls were made thinner, and the load was transmitted to the concrete and the stone. If that was the case, the joint work of the stone and concrete ought to be ensured. This was obtained by laying long cross bondstones through the entire wall width, in every third or fourth tier. These walls also stood well to earthquake shocks.

Finally, our restless 20th century saw the last stage of improving, I would like to put this word in quotation marks, the ancient three-course masonry which is now called the "midis" masonry. After the revolution and civil war, at the time of postwar devastation, the city of Leninakan was restored. To erect walls, the "midis" stone masonry was widely employed, which as if continues the strong ancient antiearthquake masonry with a homogeneous core of a fairly plastic material. Unfortunately, neither in its ideas, nor implementation, the modern masonry had anything in common with the ancient masonry. The idea of the three-course masonry was carried out in the modern masonry to the point of absurdity. It was 30 to 40 cm thick and consisted of two parallel course of stones with a small thickness of cement used as the bond between them. Bondstones were laid in rare cases. The whole structure (design) was unreliable, brittle, of low strength. The "midis" masonry behaved accordingly during the earthquake of 1926 in Leninakan. Brittle walls of this masonry collapsed into individual stones, unable to withstand dynamic effects. After consequences of the earthquake were examined, the use of this masonry was prohibited. The sorrowful lessons of the earthquake of 1926 in Leninakan were quickly forgotten and the "midis" masonry was reused, though many people knew that it must not be done. Later on, much was told and shown how universal was the collapse of stone walls and how many victims there were in Leninakan and Spitak during the earthquake of 1988. Why was not the experience of ancient architects used? Does anybody know why the lesson of the earthquake in 1926 did no good? These are questions to be replied by sociologists and government institutions.

The rocky earth of Armenia was too often shocked by earthquakes and Armenian architects could not, but be aware of it. They have devised many techniques aimed at ensuring the seismic stability of ancient buildings. Let us consider some of them.

Like the case was in the palace of Knossos and the city of Rome, Armenian architects used squared timbers, performing the function of seismic-stability belts, to reinforce stone walls and vault bases in order to make them flexible. Like the purpose of barrel hoops, the function of seismic-stability belts is to tighten a building into a single whole for it not to collapse. In some Armenian monumental structures the belts are done in the form of stones with hooks running along the entire perimeter of the building.

Like in all ancient buildings, in Armenian architecture corbeled systems above door and window openings were very popular. We may say for sure that Armenian systems displayed enhanced reliability. There were lots of them and not a single door opening without its unique make, though, generally, they practically shared a similar principle. Figure 73 shows the portal of the small church of Our Lady in the monastery of Makaravank, the 12th century. The figure shows that the corbeled system consists of two elements. This, first of all, is a semicircle- or lancet-shaped plate. It is again done skillfully, like in the Lion Gate: the plate is thickest at the point where the bending moment is greatest, at the midpoint of the span. From the top, the above-door plate is protected against the above load by an arch. The design of arches in Armenia had specific features of interest. Though these arches were curved, they were not built of similar key-stones; the builders tried to reduce the number of elements comprising the arch and assembled it of a few curved beams. This added to the reliability of the arch in case of earthquake shocks, reducing its risk to collapse. Moreover, the stones comprising the arch had a tooth to prevent their falling down in structure displacement. And now one can see the contours of arches, which remained intact after earthquakes, above the ruins of ancient buildings against the blue sky.

Now a few words about the shape of the well-known peaked ribbed Armenian domes. The first Christian churches had wooden

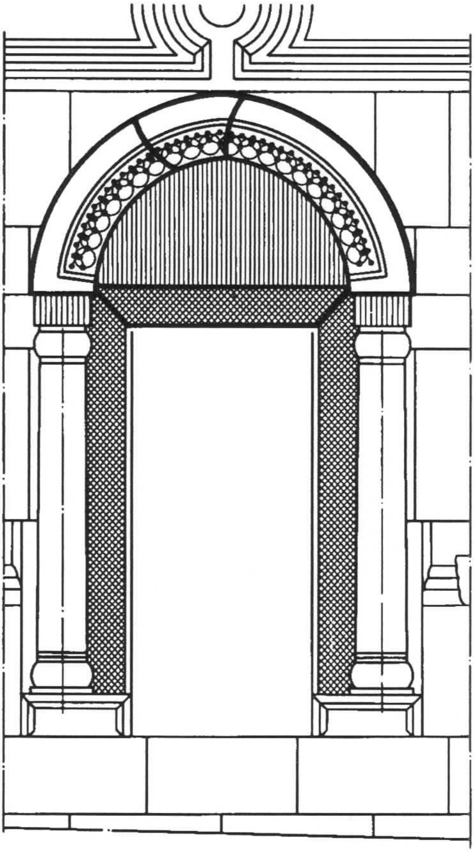


Fig. 73. Relieving system of Armenian portal

roofs, which is good from the viewpoint of seismic stability. The stone vaults were substituted for wooden roofs in the 5th-6th centuries. The roof of these vaulted ceilings was made of mortar-laid tiling. By the 10th century, when the church construction was resumed after it had been interrupted by the Arab dominion, the tiling was ousted by thin stone plates. Tiling was convenient to cover any surfaces, including curved ones; with stone roofs, cone shaped domes were erected with a straightline generatrix (Fig. 74). The weight of these domes was far greater and builders had to

Fig. 74. Ribbed Armenian dome

show concern for reducing the weight by lightening the dome fill. Embedded in the fill were clay vessels placed in turn along the vault, bottom up, bottom down, the way Roman builders did. The dome was also ribbed to the same end, i.e. to reduce its weight. At the same time, the ribs made the dome stronger and more rigid.

In order to remind you once more about the importance of properly selecting ground conditions to provide seismic resistance of buildings, I will give examples to show the behaviour of churches during the 1988 earthquake in Armenia. Very likely, the secret of choosing a site for the construction of a monumental edifice was lost in the 19th century. A group of churches built in Leninakan during the past century was situated in the centre of the city, around the square of Mayskoe Vostanie (May Uprising). This low-lying part of the city was formed by soft ground layers which, being wetted, practically completely lost the load-carrying capacity. Because of poor selection of the construction site, the largest edifice—the temple of Saviour—collapsed during an earthquake. The cause of the temple failure was a sewage tunnel built near this temple at our time. Water losses from this tunnel wetted the ground under the temple provoking nonuniform settlement and associated damage. From the professional point of view the ruins of this temple were curious to look at.

The rear wall with part of a large central bulky dome survived. The crack-formed surface of this dome showed rubble filling on a strong lime mortar. To lighten the dome, a fill was made using the light tufa. The central part of the edifice under which the ground wetting was most intensive collapsed. A narrow segment of the wall with a door miraculously rose high above the ruins. Why just this part of the outside walls has survived is an enigma, though it is known that Armenian builders attached great importance to the stability of the door and window apertures in case of an earthquake. There is one more curious detail. The small side domes fell down from the roof height and did not crack. This is how strong the lime mortar was.

Another church, Astvatsatsin, built in a higher site than the temple of Saviour practically survived. In this church only four side small domes had their base broken in parts and fell down. There is an assumption, very close to truth, that these four domes performed the function of antiearthquake protection devices. The church building with four bulky side domes raised by thin drums above the church roof had its natural oscillation period, probably, close to that of the earthquake action. During the earthquake the church was violently shaken due to the proximity of the natural oscillation periods of the earthquake action and the edifice. The little domes broke off, and the church structure at once changed into a rigid one. The effect of the interaction between the ground and the building during an earthquake decreased. The result was the church survival.

Both the ground base and foundations were of importance in improving the earthquake resistance of the structure. Probably, no specific aseismic methods were provided in the foundations of Armenian monumental edifices. As usual, the foundations were sound and strong, though the temple of Garni was built on a rigid stage. There is also a legend that the Echmiadzin cathedral was built on a sand pillow to make it resist the earthquake effects, but I failed to obtain trustworthy information about it.

In addition to the cross-vaulted system supported by pillars, in the ancient architecture of Armenia a specific system of columnless ceilings was employed in the 12th-14th centuries. The structural base of such a ceiling was represented by couples of intercross arches forming a framework that supported the dome (Fig. 75). This structure made it possible to ceil rooms of considerable area. Note that all the above domes were made in a set with framework

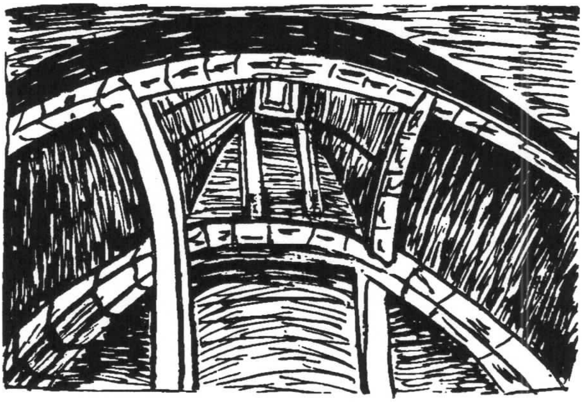


Fig. 75. Arched skeleton supporting a dome

systems. All of them proved resistant to earthquake effects. An outstanding example of the Armenian architecture is represented by the temple of Gandzasar in Nagornyi-Karabakh, which concentrates everything that has been accumulated during several centuries. I was lucky to be in this temple and was struck first of all by the details of this structure. The facing stone plates were precisely fitted to each other, the curved blocks intimately contacted each other and formed two couples of intercross heavy arches carrying the church vault, and the locks of the roof stone plates accurately fitted each other. My impression was that if the building were disassembled into separate stones, it would be easy to reassemble the temple, so accurately the stones had been fitted to one another, and each stone could be returned exactly to its place. High workmanship allowed the temple to stand more than 700 years without restoration; anyway, I was told about this by local inhabitants. As to me, I can testify to the fact that the temple was far from an ancient mossy structure with cracked walls and ceilings going into pieces. The design of this temple deserves some talk.

The construction of the church of John the Baptist began in 1216 and was completed in 1238. A vestibule finished in 1266 was attached to this church at the western side. Both these buildings formed one structure erected on a five-step stage-stylobat of rubble concrete on a lime mortar. The church was ceiled by the cross-vaulted system resting on four pillars tied with the walls to ensure good stability of the whole system. Lancet arches were spanned between the pillars. Another system was used to ceil the vestibule built somewhat later. Its vault was borne by two couples of intercross arches. Besides, it points that the architect was in the throes of hesitation during the construction work. He propped up the longitudinal arches near the edge, each by one column, and added herein one more internal arch. It was not good from the standpoint of seismic stability to erect an arch of unequal rigidity. Neither it was good that the church and vestibule buildings were not separated by an antiearthquake joint. In all other respects, the building was probably so strong that the temple of Gandzasar stood for more than 700 years without damage.

Finishing writings on the earthquake resistance of numerous ancient monumental structures of Armenia, I cannot help telling you about one more Armenian temple, a wonder either of the East or West that can be dreamed about only in sleep. This is Zvartnots, the temple of Vigil Forces whose construction was started in 643, the money required being collected by the people. For the general view of the temple, see Fig. 76a; its ground plan appears in Fig. 76b. Several more centric temples with an axial symmetry were built in Armenia and Georgia: Ishkhani, the temple of Gagik in Ani, the cathedral in Bana; all of them collapsed. The temple of Zvartnots survived more than 300 years and failed at the end of the 10th century due to an earthquake. The cathedral in Bana turned out to be most perfect in design. It was destroyed only in the 19th century during the war.

Let us analyse in short the unique structure of this temple. The figure demonstrates that it is a centric building consisting of three barrels placed on each other. The lower barrel is about 36 m, the middle one—about 26.0 m in diameter, and the total height is about 45 m. It is well thought out in the temple structure how to transmit and distribute the loads. The first largest and highest barrel is formed by a round wall (Fig. 76a). The second barrel, smaller in diameter, rests on a ring laid of stone-lime mortar. The top view diagram of this ring is shown in Fig. 76c. This element of the structure is most interesting. The ring is 82 m in the outer

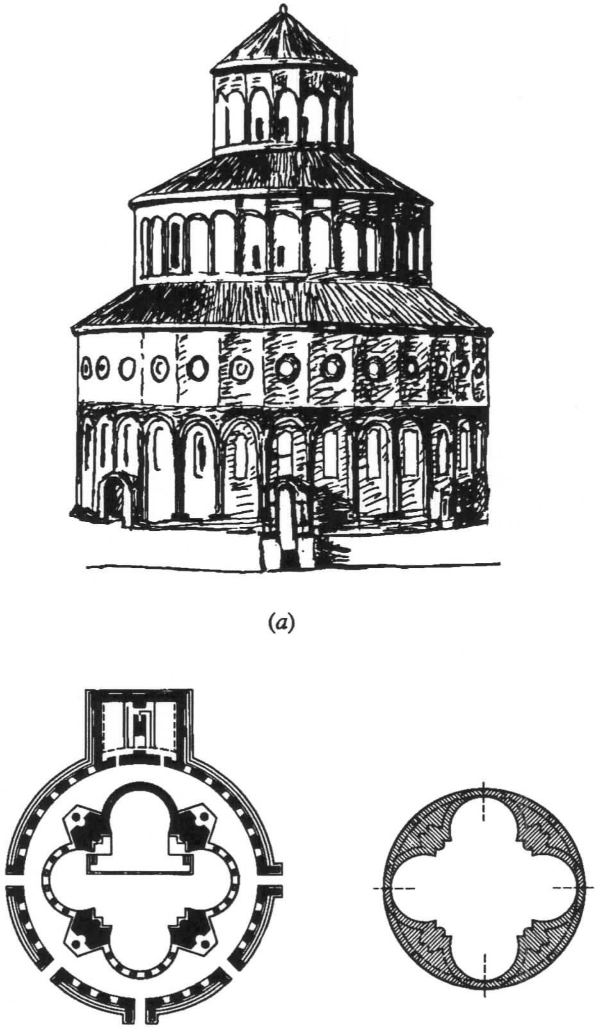


Fig. 76. The temple of Zvartnots:
(*a*) general view; (*b*) ground storey plan; (*c*) temple base ring

circumference length. Its width varies from 2.75 m to 6.5 m; the wall thickness of the ring is 1.5 m. The lime mortar is so strong that it stands well where a stone does crack. The ring itself rests on four pillars passing through it and supporting the top small barrel with a cone dome. In addition to the pillars, the same ring also rests on all columns and walls of the ground storey to connect them to each other. This strong ring forms the key element of the structure. First, it supports the second (from the ground) storey; second, it is the antiearthquake belt connecting pillars, columns and walls of the ground storey into a closed spatial system. The structure of Zvartnots turned out to be a light and proportional building, the more so that builders tried to lighten it, using tufa and pumice-stone as concrete aggregate and embedding hollow pots in the walls.

Some components of this temple are of interest. Examples are columns that were made of three elements: the base, the shaft and the capital, each of them produced of solid stone. Lead sealed metallic cramps were used to connect them. This was a traditional ancient technique due to which the columns had plastic hinges that worked only in compression.

Disadvantages of this structure may also be observed. The uniform rigidity distribution is absent at the level of the ground storey. Figure 76b demonstrates that a kind of tower is attached without a joint to the barrel of this storey through its height to house stairs leading to the top gallery. Certainly, it affected the uniformity of masses and rigidity distribution. There is one more dangerous point in the temple structure. The above-described monolithic ring rests on the pillars and columns through eight large-span vaults whose arches forming a circle have double curvature, exactly like in Pantheon, and protrude beyond their plane at least for a meter. It is clear that this shape of vaults will cause their twist, which is far from good for such a brittle material as stone. However, should this structure be unreliable, it would fail in the course of construction, but the temple survived for 350 years. Some investigators try to find out the causes of the Zvartnots failure. What were the errors? Maybe the quality was poor, maybe 22 m pylons were a bit too long, maybe the columns were insufficiently strong, or maybe something else. I agree with

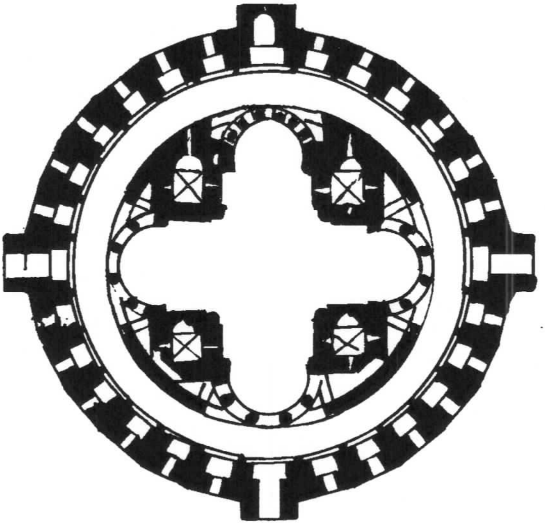


Fig. 77. Plan of the temple in Bana, the type similar to Zvartnots

T.A. Marutyan who voices the opinion that there were no errors, everything was well thought out. The only factor that affected the temple was the three-century dominion of the Arabs during which the temple fell into decay. During this time there was a fire; maybe the temple was used as a stone quarry, and this mismanagement led to the collapse of Zvartnots.

The temple in Bana that resembled Zvartnots in many respects had different dimension proportions. Its lower barrel was 38 m in diameter, i.e. a bit greater than that of Zvartnots, but the height was much less, 30 m in all. The plan diagram of the temple in Bana is shown in Fig. 77. Comparing this plan with that of Zvartnots presented in Fig. 76b, two essential differences leap to the eye. First of all, the outside circular wall in Bana was much stronger since it consisted of a number of counterforts. The four underdome tiers that became support towers were stronger as well. The joint work of the central piers and outside walls provided a reliable base for the whole edifice. The dome was also of moderate dimensions, 8 m in all.

We have acquainted ourselves with the architecture of ancient Armenia from the viewpoint of special antiearthquake measures taken. In the architecture of Georgia, which developed under the same conditions as Armenian architecture, the principal approach to the earthquake-proof construction was the same, for which reason I shall not consider in detail the individual monuments of Georgian architecture, but make some comment only.

In the 6th-5th centuries B.C. use was still made of the cyclopean masonry laid of huge stones, but without thorough fitting we saw in Mycenae. In the 6th century B.C. a more skilful masonry, from the seismic stability viewpoint, developed utilizing regular cut stones dry-laid and secured with wooden pins of the dovetail type, or iron cramps sealed with lead. This cut-stone masonry was employed to erect walls and towers as a whole or only the foundations, laying the walls of adobe air-dried bricks reinforced by wood. During the subsequent centuries till A.D. lime mortar and sandwich (three-course) walls became popular.

The first architectural monument of Georgia completing the period of search for the solution of tasks set by the Christian religion was represented by the temple of Dzhvary in Mtskheta, the ancient capital of Georgia. The problem of creating a vast internal space was solved in this temple which was erected in 586-604. Its central space was spanned by a dome raised on an octahedral drum. Through the drum the dome was supported directly by the walls. Soon, between 626 and 634, another temple was built in Tsromi whose underdome space was substantially extended, since the dome was supported by four stand-alone columns. The construction of the temple in Tsromi marked the development of cross-vaulted systems in the architecture of Georgia. The edifices built according to this system were structurally more complicated and, hence, less resistant to earthquakes compared to the structures where the dome was supported directly by the walls.

It was already then that the idea of creating aseismic belts arose. Structurally, the belts were made in the form of cut stones coupled to each other with the aid of cogs made in them. As it should be, the tiers of such cut stones were located in the upper part of buildings where the dome produced maximum thrust [3, 27, 28, 29].

Continuing our trip in the Caucasus, I suggest to visit the North Caucasus regions in order to acquaint you with folk traditions. While significant temples of Armenia and Georgia were built by highly educated and experienced architects, the watch and household towers in the North Caucasus settlements were built by craftsmen familiarized most often with the traditions of their native region. Here we also have much of interest.

Towers in Mountains

The construction of towers in the Caucasus has been known for a long period of time. There were watch, dwelling, chapel, and mausoleum towers. Stone was the principal construction material, the mortar materials were represented by lime and clay. Of all structures in the mountain settlements, the towers, watch towers in particular, were unique structures. They were built by the best craftsmen using large, well selected stone blocks. Not in vain, there was a saying that the stones of one tower were enough to build a settlement, but a tower cannot be erected of stones of the whole settlement. The materials were thoroughly selected; weathered, cracked stones were rejected. The towers were expensive and could be built only by well-to-do families, though they were made of local materials and by local craftsmen. The towers were mainly rectangular, seldom round, though the advantages of round towers from the standpoint of defence were incontestable, as well as from the standpoint of earthquake-proof construction. Naturally, the rural craftsmen did not take any antiearthquake measures. They met this requirement utilizing the materials available and built strong and stable structures, using the historically evolved traditional architectural forms. I was always delighted at these towers, in particular those resembling warriors wearing helmets, watch towers associated with legends and romance of blood feud. In spite of their simplicity, these towers are pieces of true architecture. Here are some examples.

In Dagestan village of Itsari there stands a watch tower in the form of a truncated cone (Fig. 78), which is unusual for these localities. It was erected in the 15th century by local inhabitants, when their prince transferred his residence from

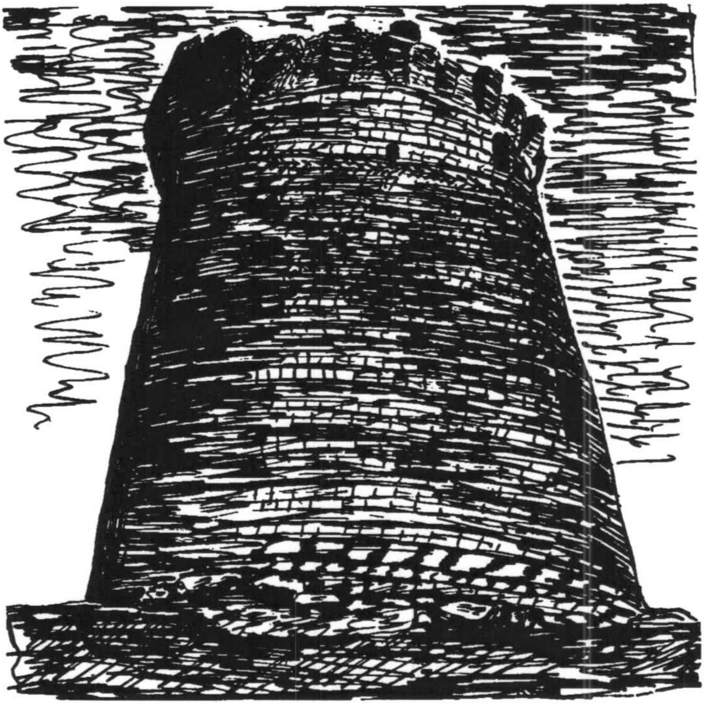


Fig. 78. Truncated-cone tower in Dagestan

their village to another site, and the villagers had to rely in defence solely on themselves. The tower shape and technique of laying stone materials point to the fact that its build-ers were skilled in the stone work, had a good understanding of fortification, and even had an idea of the statics of structure work. The cone shape of the tower provides its general stability. It shares masses and rigidity in an ideally uniform manner. The base part of the tower is built of large stone flat-laid blocks. The middle part of the tower is erected of alternating courses of upright and flat-laid stones to ensure uniform properties of the stone masonry. The walls become narrower with height. Next we shall consider one more earthquake-resistant tower, but of the traditional style.

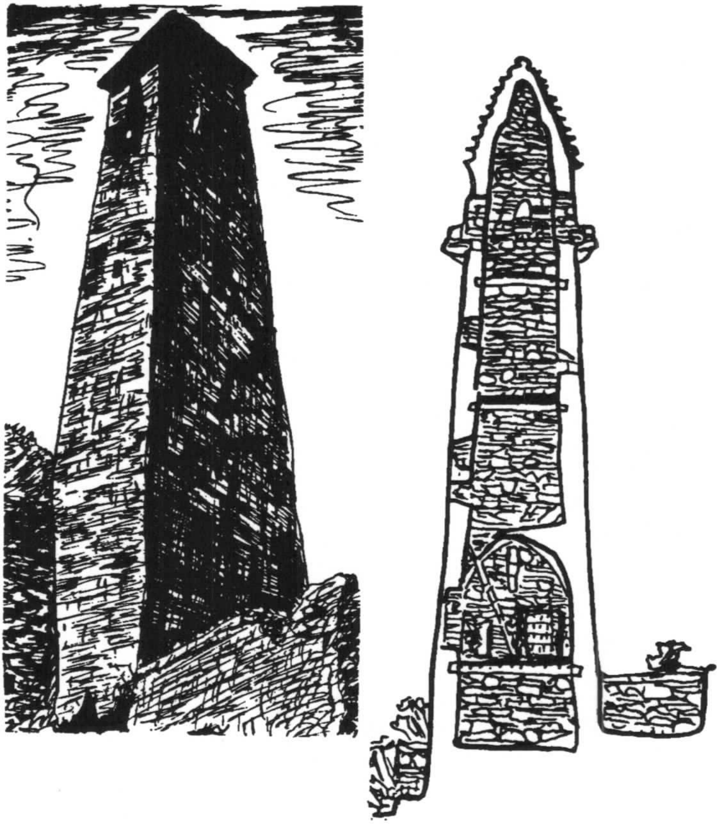


Fig. 79. General view and section view of Vaynakh watch tower

The Vaynakh watch tower of the classical type is shown in Fig. 79. These towers were from 20 to 25 m in height and from 5 to 5.5 m in the plan side. The number of storeys was from five to seven. The wall thickness decreased with height, and the walls were simultaneously inclined inward. As a result, the tower silhouette showed clear narrowing. To my mind, whatever the motives, builders tried not only to provide the tower symmetry, but also to reduce the tower weight and to lower its centre of gravity, thus making the structure resist earthquakes.

The lime mortar used in the masonry work was sometimes very strong. In Dagestan clay mortar was employed, which badly affected the masonry strength and did not allow inward inclination of the tower walls. The most perfect Vaynakh towers of the Great Caucasus had stepwise tapered roofing to improve their architecture and protect them against precipitation. The floors were also made in the form of a closed four-sided pseudo-vault by corbeling the stones; this created rigid disks along the tower height. These disks performed the function of seismic-stability belts. It turned out that the Vaynakh towers met almost all the requirements of earthquake-proof construction. The tower masonry workmanship was tested in a specific manner. A mouse was let in, and if it escaped, builders were deprived of the prize—50 cows. The rock in the tower base should not have cracks. This was also tested in a very simple way. A pool of milk was spilled, and if the milk was absorbed by the soil rather than dried up, the site chosen for the construction was rejected. By the way, layers of sand were observed under the foundation blocks of watch towers.

The household towers used wooden storey floors and were not so perfect from the viewpoint of seismic stability for various reasons: a weak mortar, heavy walls, nonuniform masonry, the absence of rigidity disks, and unreliable clay roofing.

The traditional tombs found in groups and separately in the mountains of Ossetia are remarkable in appearance and perfect in structure (Fig. 80). These are small square (in plan) structures whose walls are slightly inclined inward and gradually turn into a high vaulted roof. Stone plates protruding outward are fitted in the joints between the stones of the vaulted roof, which makes the Ossetian tombs look somewhat like the multistage pagodas of Indochina. Generally, nearly all rudiments of the construction techniques can be found in the traditional popular structures, which later on were improved to be employed in the monumental construction of palaces and temples, ensuring their strength and long life. They include strong walls and foundations, various corbeled systems, vaults, and many other factors. So, the popular and monumental construction techniques are of the same origin. To continue our trip, we shall set off for the Transcaucasian plains [30, 31].

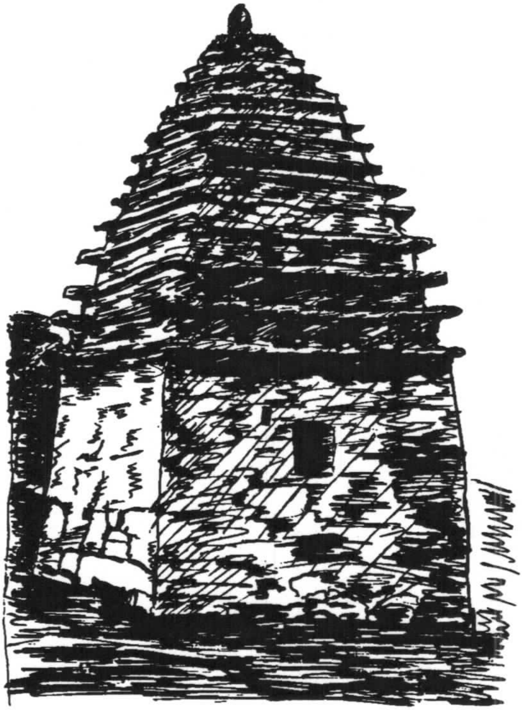


Fig. 80. Pyramidal tomb in Ossetia

Azerbaijan Architecture

Earthquake storms occurring in the depths of the Caucasian mountains shake this large plain representing the central area of Azerbaijan. On three sides the plain is surrounded by mountain ranges. On the eastern, fourth side, the plain is washed by the Caspian Sea into which the peninsula of Apsheron deeply plunges. The variety of natural resources, stone abundance in the mountains, clay in the plain, historical traditions, another faith, all this gave rise to other architectural and construction tasks and their solutions specific for these areas. Certainly, there are relations with other peoples in the Caucasus, but we can also see traces of close relations with peoples of Central Asia. People settled on the

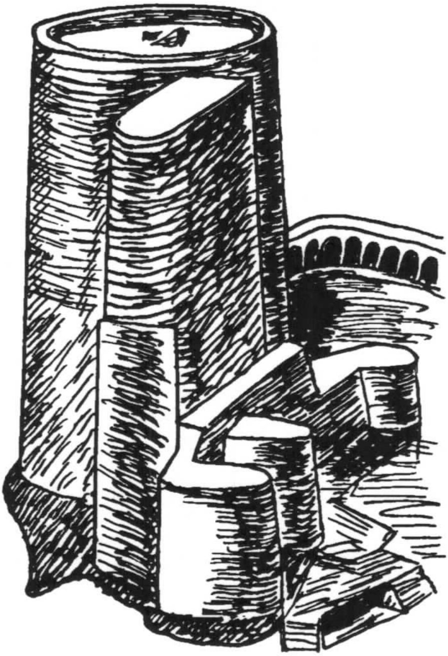


Fig. 81. Asymmetry of the tower-type temple of fire-worshippers

fertile soils of this plain long ago. Found were settlements of settled cattle-breeders built in the 6th-4th millennia B.C. These settlements comprised round cabins vaulted by air-dried bricks. The accumulation of construction experience started at that time. But we shall not go so deep into the past. We shall not even deal with the Midian tribes that settled on the territory of the present-day Azerbaijan in the 9th century B.C., who later on created a state that fought against the troops of Alexander the Great. Midia was one of the fire-worship centers and had relations with Assyria, Babylonia, and Urartu. It is the region from which the architecture of structures we shall consider later originates. We shall study the individual monumental structures and examine them from the viewpoint of seismic stability.

We shall start with the Virgin tower that can be admired in the city of Baku. Figure 81 presents its general view and cross-section.

This mysterious tower greatly differs from other watch and religious structures of Azerbaijan. On the one hand, it is a kind of tower-temple of fire-worshippers, and, on the other, it is a watch tower. It is called the Virgin tower since it was never captured by any enemy. According to some sources, the tower was erected in the 8th century B.C. and, according to other sources, it was built in the 12th century A.D. The purpose of its counterfort, which is asymmetrically attached to the round tower, is absolutely not clear. The list of unintelligible facts could be continued, but it is better for us to consider the design of the Virgin tower.This tower is an eight-storey structure in the form of a truncated cone standing on a rock slope. At one side its height (the parapet inclusive) is 32.0 m. At the other side, its height is 35 m. As the figure shows, a strong counterfort is attached to the tower on the side where the tower could slide down along the inclined rock. The counterfort is , in turn, supported by a wall with small counterforts. This indicates much concern of ancient builders for the stable base of the tower. The tower walls are unbelievably thick, from 5.0 m at the foot to 4.0 m at the top. The walls are laid of limestone blocks on a strong lime mortar. The internal space of the tower is divided into eight storeys by plane stone domes. The specific ribbed external surface of the tower is formed by alternation of jutting and sunk masonry courses.

It follows from the above description of the tower structure that the tower is a very rigid, extremely heavy bulk with uniformly shared masses and rigidity, except for the counterfort. In fact, this side counterfort may be neglected, since its twisting effect in case of an earthquake is absent due to the immense thickness of the tower walls and a huge twist-resisting moment; so, this asymmetry is of no danger to the tower integrity. Because of its immense weight, this tower resembles Egyptian structures. In any case this weight, well designed base, strong masonry, and shape imparted high seismic stability to the tower.

Now we shall have some talk about a conventional watch tower many of which were scattered over the peninsula of Apsheron. Survived in a settlement named Mardakyan is a recently restored round tower in the form of a truncated cone, 16.0 m in height, 7.6 m in the foot diameter, whose sectional view is shown in Fig. 82.

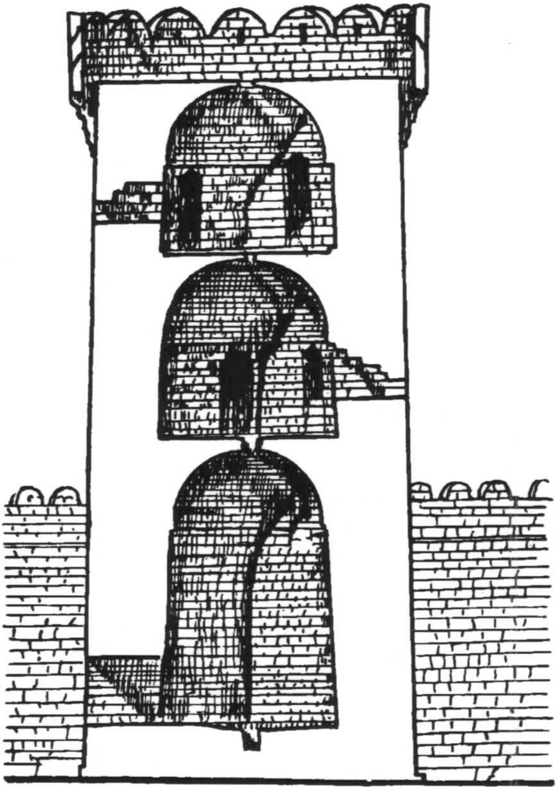


Fig. 82. Design of bulky stone watch tower

The tower is laid of the local limestone on a highly strong lime mortar. The figure shows its internal space divided by spherical domes of the same material into three storeys. The tower was erected in 1232. The earthquake resistance of this rigid, perfectly proportional structure is clear without explanations.

Later they began building rectangular towers in castles. A rectangular castle reinforced by round columns at the corners, which was built in the 14th century, survived in the same settlement of Mardakyan (Fig. 83). Here use was also made of stone masonry on a lime mortar, but the internal floors were made

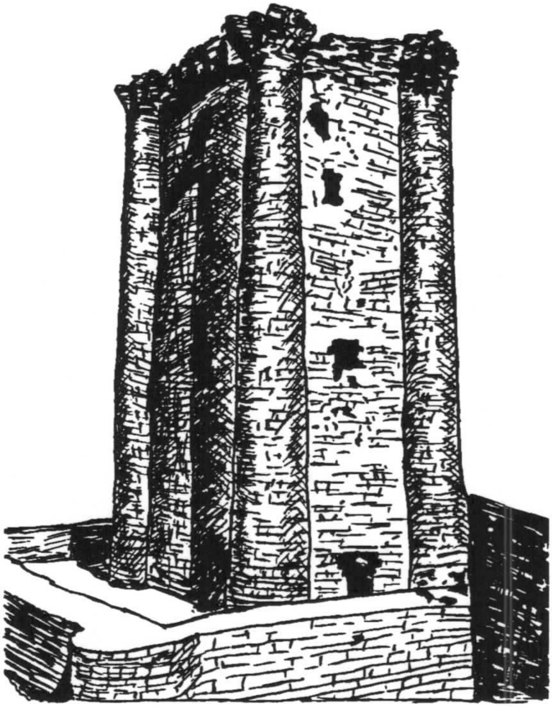


Fig. 83. One more watch tower

on the basis of timber beams. In the above watch structures the resistance to earthquake shocks was ensured by their moderate dimensions, mass and rigidity distribution symmetry, strength of masonry; weight reduction, and the more so seismic insulation, were out of the question. Now let us consider some memorial structures of more complicated design in compliance with more complicated architectural forms.

In 1162 the building of the burial-vault for khoja Yusuf, the head of sheikhs, was completed. A general view, cross section and a plan of this burial-vault are presented in Fig. 84. We see a conventional structure of that time, but how perfect it is in design and workmanship. As for the architectural proportions and

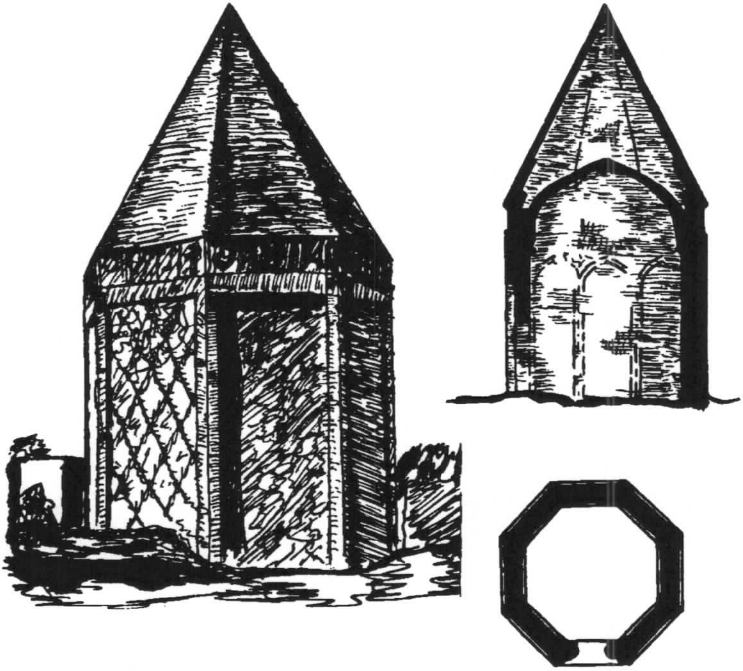


Fig. 84. Yusuf mausoleum, general view, plan, section view

resistance to earthquake shocks, the mausoleum is perfect. It is built of burnt bricks on a strong mortar. Note the octahedral plan of the mausoleum. This is almost an ideal form from the viewpoint of resistance to earthquakes. The walls are moderate in thickness, reinforced on the outside by thickenings in the form of ribs forming as if an external skeleton. There is also an internal skeleton roofed by lancet arches. The wall above these arches is thickened forming a support ring for two domes, external octahedral and internal lancet domes. The octahedral walls smoothly develop into an octahedral dome. The generalizing principle of earthquake-proof construction stating that the construction must prevent stress concentrations anywhere during an earthquake has been met herein. Certainly, the mausoleum presents a rigid structure.

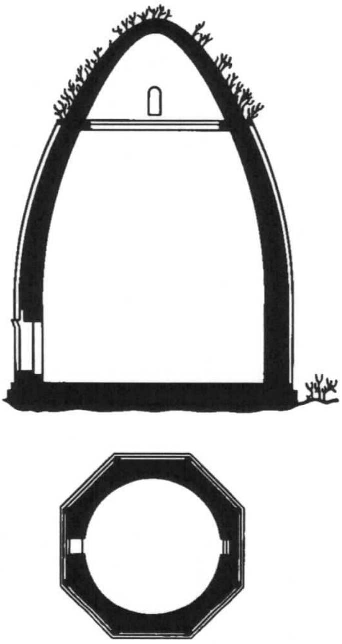


Fig. 85. Shell of Melik Ajar mausoleum

I would like to draw your attention once more to how the ancient builders combined knowledge, the use of traditions accumulated, and creative approach to their structures. A curious example is a fanciful, unique mausoleum of the 12th century that stands near a settlement named Dzhidzhimli. Its shape resembles a clay hut of the early Bronze Age. The mausoleum, however, was built, using the construction techniques of its time. For the sectional view and plan of this mausoleum, see Fig. 85.

The mausoleum is laid of coarsely cut stones and faced with large finely dressed plates bonded by a strong mortar. The mausoleum walls are gradually inclined inward, and it is crowned by a parabolic dome. Herein the outlines are so streamlined that nothing can be said about unequally shared masses and rigidity. The seismic stability of the mausoleum is ensured by the rigid, strong, and light shell of this structure.

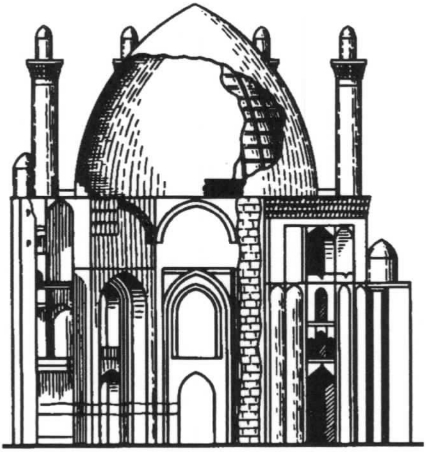


Fig. 86. Earthquake-resistant dome of Oldzhaitu mausoleum

As the next step, we shall consider a more complicated structure of an intricate design. The unique structures of Azerbaijan were done at the "world standards" level, as would be said today, employing the advanced construction technology of that time. I said once that studying the ancient history one is constantly surprised at the informativeness of seemingly most remote peoples, particularly in the field of construction technology. An example is a monument of the Azerbaijan architecture, the mausoleum of Oldzhaitu Khodabende (1307-1313) that survived in Iran, in Sultaniya. It is a most distinctive, outstanding monument of architecture, and, at the same time, it has absorbed much of the best created in the construction technology by that time. Shown in Fig. 86 is a sectional view of the mausoleum built of bricks. First that attracts your attention in the figure is a high lancet dome comprising two shells. The dome is 23.3 m in diameter and 20 m in height. The total height of the mausoleum hall from the floor to the dome key stone is 51 m, i.e. it is a gigantic structure. The lancet-shaped dome and its double shell connected by ribs forming a skeleton system resemble both the dome of the Florentine cathedral and the dome of St. Peter's basilica spoken about before. These lancet domes were used to reduce the dome thrust. To the same end, the dome shell was a double type to reduce the dome weight, saving its strength and rigidity. It is interesting that the mausoleum in Sultaniya built much earlier than the Florentine cathedral has a more perfect dome. In the cathedral both shells of the dome are not equivalent. The inner shell is load carrying, while the outer shell is protective. In the mausoleum both shells of the dome are equivalent in their joint work, like in St. Peter's basilica, which is a great achievement of those who built this mausoleum. The next important point associated with the seismic stability of the dome roofing is the smooth joint between the dome and the walls. In this mausoleum this problem is solved in a brilliantly simple way. The huge ceiled hall is a regular octagon. To join an octagon to a circle is not difficult. Next, the dome thrust must be properly taken. This problem is also brilliantly tackled at a high engineering level with a large margin of safety. First, in the lower part of the dome there is an antithrust monolithic ring reinforced by three metallic hoops. Second, the probable thrust is supported by the vaults of the gallery encircling the dome base. Besides, the mausoleum corners are additionally loaded by minarets, which is also an antithrust measure. The vaulted galleries in the base of the dome are techniques widely used in the buildings of Central Asia, for example, in the mausoleum of sultan Sanjar in Old Merv.

Thus, in the mausoleum considered a set of measures is utilized that are aimed at taking up the thrust of a large dome. These include a lancet-shaped dome, double lightened dome, reinforced support ring, smooth joint between the dome and the walls, vaulted encircling gallery, additional loading by the minarets. Even at our time we could not do more, unless we erected a makeshift inflatable dome. The dome of the mausoleum in Sultaniya still survives.

As far as the structure of the mausoleum is concerned, the following can be added. The dome rests on the walls where brick arches are embedded, like in Pantheon, but now lancet-shaped, and the walls are lightened by deep niches also vaulted by lancet arches of brick. This is an example of high construction art achieved by Transcaucasian architects many centuries ago. Now, as usual, some comment on this region, and we shall go further towards East, deep in Central Asia.

A group of mausoleums was built in the basin of the Araks river in the 13th-14th centuries where clay jugs were embedded to lighten the domes, like it was in Rome, Byzantium, and Armenia.

Other seismic-stability improvements of that time may be named. The brick masonry was reinforced by timber beams that were also placed above the entrance apertures. We have already discussed the purpose of it.

Along with the lime mortar, use was made of looser mortars (locally called "gyazhevye" mortars). The lime mortars are harder and more brittle than gyazhevye mortars that are more plastic and stronger. It must also be said that the cement mortars are still more hard and brittle than the lime mortars. Naturally, when it was necessary to impart ductility to the brick or stone masonry, gyazhevye mortars were employed, thus increasing the thickness of the bedding joints between the brick courses. This purely aseismic technique was widely used in the architecture of Central Asia. Also employed were brick belts in the stone masonry, as it was done in Byzantium. Almost all structures of Azerbaijan featured the property of centricity. Underground vaults of specific, rare design were built in Nakhichevan, which ensured their survival at any earthquake shocks. The base of this structure was represented by a central strong pillar bearing the ends of the ceiling arches. Thus, the ceiling consisted of arches, and the destruction of one arch did not involve the whole ceiling [2, 4].

After getting an idea on the earthquake-resistant construction of ancient Azerbaijan, we shall go further to Central Asia with which Azerbaijan has close relations. Examples are splendid mausoleums decorated with heavy portals that appeared in the 14th-15th centuries under Timur Lenk and his descendants in Central Asia. These portals affected the centricity of those structures and, hence, reduced their resistance to earthquakes. At the same time mausoleums with attached portals were built in Azerbaijan.

Seismic Stability Of Architectural Monuments In Central Asia

In Depth of Millennia

We have reached one more region of this sublunar world with vast areas, complex history, and diverse traditions. The settled agriculture developed in Central Asia already in the 5th-4th millennia B.C. Small settlements appeared in oases, copper smelting developed, and contacts with Sumers were established. In the 3rd-2nd millennia B.C. an association formed in the south of Central Asia whose culture was conventionally called Altyn-depe. The monumental architecture of that time is known for a large religious complex dedicated to the lunar God, including a four-step tower 12.0 m in height and 28.0 m in length, very like the ziggurats of Mesopotamia. In the 6th century B.C. the first state, Bactria, developed which soon, like all other oases of Central Asia, was joined to the Persian power of Achaemenids.

Here in Bactria, it might be worthwhile to stop and acquaint ourselves with a circular structure which we have not yet seen before. This is a temple-fortress named Kutlug-tepe, the 5th century B.C. (Fig. 87a). The inner diameter of the ring is 22 m. The walls are 2.5-3.0 m thick laid of bricks on a clay mortar. The height of this two-storey structure is 6-7 m. There is a go-round passage about 3.5 m wide inside. The ceiling is flat supported by timber beams placed on the circular walls. It follows from this description that, in contrast to the above rigid ring of Colosseum, the temple of Kutlug-tepe may be presented as a ductile ring with plastic properties. This ring can be, probably, deformed without

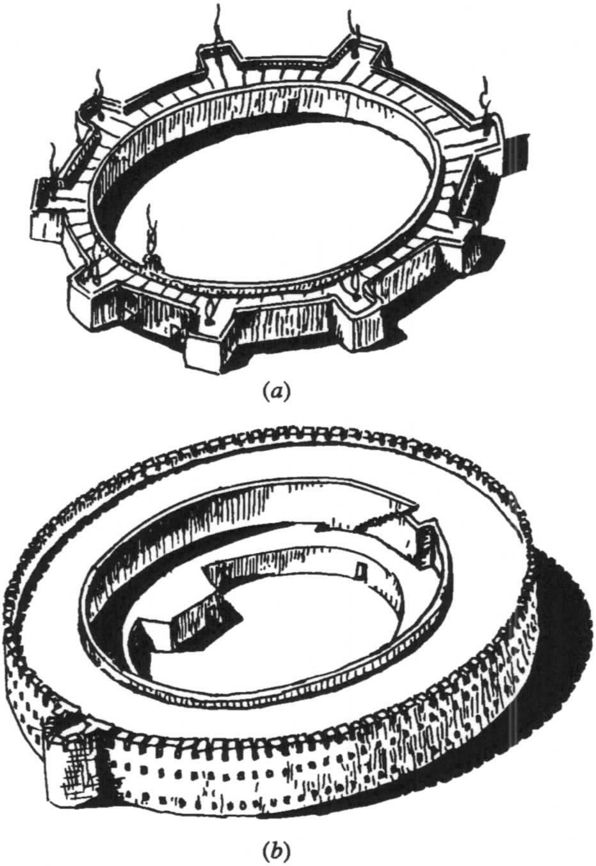


Fig. 87. Circular structures:
(*a*) temple fortress Kutlug-tepe, the 5th century B.C;
(*b*) temple Dashly-3, the 17th century B.C.

damage, like the case is with the Earth surface during an earthquake. The shape of the temple is stable, and it practically meets all principles of seismic stability. This is not the only circular structure of that time. Other temples, like this one, were built. They were associated with honouring the solar divinity Mitra. Figure 87b shows the round temple Dashly-3, the 17th century B.C. The brick walls of this circular temple are very skillfully reinforced with additional counterforts. Being convinced of the construction skill that already existed in Central Asia at those very ancient times, we may continue our trip along the river of time.

The power of Achaemenids was finally overthrown after the defeat at Gangamls in 331 B.C. inflicted by the Greek troops of Alexander of Macedon. In 305 B.C. Central Asia was included in the state of Seleucidae with the capital in Babylon. In 250 B.C. an independent mysterious Greek-Bactrian state was formed; Parthia and Khoresm became independent, and in the 1st century B.C. they were included in the largest empire of the ancient world—Kushan. Henceforward, in the same manner, states appeared and disappeared in the lands of Central Asia, socio-economic formations changed, entire nations emerged and vanished, bringing into being various architectural forms. It is not our task to study all this, we shall continue studying our narrow problem of seismic stability measures used by ancient architects. To this end, we take some historic facts interesting for us and analyse them from the standpoint of modern earthquake-resistant construction. Like the case was with the Caucasus, we shall start with the 1st century A.D.

Let us go to the site of settlement known as Toprakkle situated in the Lower Amu Darya. This archeological complex comprises a well fortified town, a palace on a high stage, one more court block, a fortress, and a mysterious vast area surrounded by a bank. These are the remains of the capital of Khoresm kings. The very first active period of this capital existence falls on the 1st-3rd century A.D. Of many buildings of this town we shall consider only the High palace standing on a gigantic stage. This will be enough to have an idea of the construction technology of that time.

Studying the structures of the High palace, you get an impression that we returned to the valleys of Mesopotamia where air-dried bricks of loess clay were the principal building material, buildings were erected on special stages, and vaulted structures began to be built. Here in Toprakkle, as well as in other Khoresm monuments of that time, the principal construction material were also air-dried bricks of loess clay. All load-bearing structures were made of two types of this brick. The first, most popular, was the plain square brick, 40 by 40 by 10 cm, on an average, whose weight exceeded about 8 times the weight of the modern brick and was about 38 kg. This brick was used to lay the stages, walls and beam ceilings. As a rule, the brick made 57 per cent of the total masonry volume, the remainder being clay-sand mortar. It is clear from the above-said that such a masonry featured ductility. The other type of brick was trapezoidal in shape and found its applications in erecting arches and vaults. In addition to the shape, this brick differed from the former type in composition, which influenced its mechanical properties. Chopped straw was added to clay during production of the second-type brick, decreasing the amount of sand, to reduce the volume weight of the brick and make it more ductile. In short, a better-quality brick was used in most important elements of the structure. After this short introduction, we may proceed to the structure of the High palace.

This palace was erected on a huge stage, up to 14.3 m high, shaped like a regular rectangular truncated pyramid. The area of the bottom base was 92.5 × 92.5 m, the top area being 82.5 by 83.1 m. To illustrate the size of the stage, I can say that about 6 000 000 of huge bricks were laid to build it. The stage (platform) was made multipurpose: defence, protection against floods, extolling the king's palace and, finally, what is most important to us, protection of structures erected on this stage against earthquake waves. According to the above classification, this stage built of air-dried bricks belongs to a soft type. The buildings of the Low palace were also built on stages, though not so huge.

Now, some words about the seismic stability elements of structures of the palace placed on the stage. A sectional view of the palace walls, its foundations and stage is shown in Fig. 88. The truncated pyramid shape of the support stage under the palace adds to its resistance to earthquake shocks. In addition, the stage is embraced along its perimeter by a heavy strong wall of bricks bonded by clay mortar. The central part of the stage is represented by sandwich substructures of bricks on sand and clay (recall the sandwich substructures of Colosseum). Laid under the inner walls are ductile cushions of brick on sand to protect the walls against unequal settlements and earthquake shocks. To provide seismic

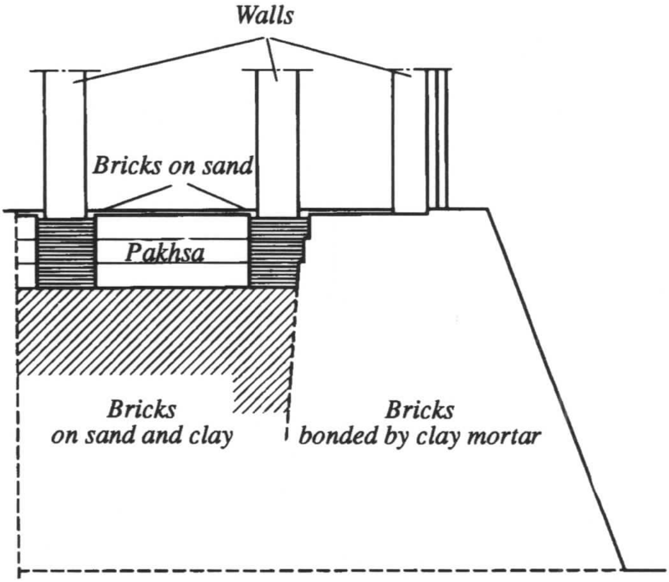


Fig. 88. Section view of the Toprakkle stage

stability, the outer wall has coupled projections at 1.8 m spacings. The ceilings of the palace are as follows. Two kinds of ceilings are encountered in the palace: a flat ceiling on timber beams and vaulted ceiling of specially prepared bricks. Interestingly, vaults in the form of an ellipse or close to it were characteristic of Khoresm buildings of that time. To enhance the vault reliability, they were laid in a few rows, which allowed some vaults to survive till now. Already at that time burnt brick was used as a facing material.

If we wander over the ruins of the High palace hall a bit longer, we are likely to encounter something else interesting for us. Look here, a course of air-dried bricks is exposed, and each brick shows traces of the human hand. The craftsman made furrows with his fingers on the side of the formed brick. It was done to improve bonding between the bricks. This is what the Greeks did roughing the joint surfaces of blocks. However, stick to the point, note one more last detail. As was said above, flat ceilings were used in the

Fig. 89. Stone base of wooden column

palace. In case of short spans, timber beams were spanned from wall to wall. Next, a counter floor of poles was laid on them, then went a course of cane coated with clay and straw. And only then there were a course or two courses of clay bonded bricks. This completed the flooring (ceiling). In case of larger spans, ancient builders erected intermediate supports, columns with stone bases. These stone bases (Fig. 89) had a bore to receive the lower end of a wooden column. This column could not come off its base in case of an earthquake. The hinge formed at the low end of the column provided its reliable work, since no bending moment could occur in the column, and it worked only in compression. It was not said above, but similar-type stone bases for wooden columns are encountered in the Caucasus, and we shall see them later in Central Asia.

There is one more example typical for the antiquity time of Central Asia. For you not to think that the ancient temples here were only circular-shaped, we shall visit Sogdian and examine another, more popular type of temples, square in plan and stepped in shape (Fig. 90). It can be found among Bactrian, Parthian, and

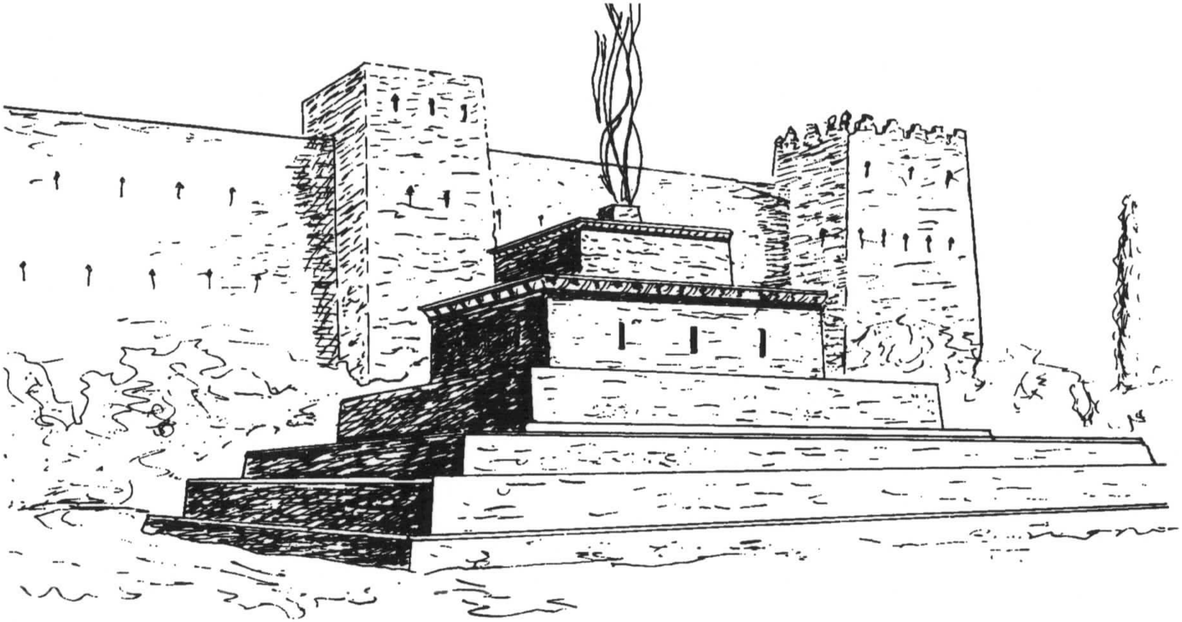


Fig. 90. Pyramid-like temple of fire-worshippers

Sassanid-Iranian architectural monuments. The temple of fire-worshippers the figure demonstrates was opened to the north of Samarkand in Kurgan-tepe. This temple is dated from the 1st-2nd century A.D.

As to its shape, the temple of fire-worshippers in question much resembles the ziggurats of Mesopotamia, and exactly likewise its base is a homogeneous stage (platform). This stage is placed on the mainland loess and laid of courses of dense plastic clay (pakhsa) and air-dried bricks (45 by 23 by 10 cm). Its dimensions in plan are 25 by 25 m and 0.7 m in height. The next steps decrease in plan and are 1.75, 1.0, 0.5 and 1.15 m in height. The material of these steps is similar to that of the bottom stage. The top platform, 15 by 15 m in size, carries almost a square structure, 12 by 11.5 m. This is the temple itself. The internal space of the temple is divided into several rooms by longitudinal and transverse walls laid of the same air-dried bricks. The sides of brick show the above-mentioned furrows—traces of the human hand made to improve bonding. The ceiling of the internal rooms is flat carried by parallel load-carrying timber beams. To my mind, it is not necessary to talk again about the seismic stability of a structure built of ductile material with a light roof, standing on a pyramide-like base of the same ductile material. Note the defence walls behind the temple in Fig. 90. Counterfort towers supporting these walls in case of an earthquake are seen.

We shall not spend time among the most ancient buildings made of air-dried bricks and go over to more perfect buildings of burnt bricks. We shall not deal with stone structures in Central Asia, as they are very rarely met [32, 33, 34].

Typical Secrets of Seismic Stability of Ancient Structures in Central Asia

Even within our recollection the lands of Central Asia were many times shaken by earthquakes, and during their eventful history, these lands underwent many catastrophic earthquakes, which is witnessed by instantly destroyed towns buried under sands up till now. Naturally, the ancient craftsmen persistently searched for methods to protect their structures against earthquakes and developed a series of structural improvements to provide better seismic stability of their creations. According to the tradition adopted at that time, these improvements were passed on from generation to generation. The architects of Central Asia arrived at the same conclusion as all their contemporaries and predecessors: only ductile and strong materials are capable to withstand earthquake shocks, provided certain rules for the structure arranging are observed. As we shall see further, these rules are similar to the above principles of earthquake-resistant construction. Recall builders of the Knossos palace who imparted ductility to rigid stone structures by reinforcing them with timbers. The seismic-stability ideas of the architects of Central Asia were similar to all architects, but the structural implementations of their ideas were very specific. Without considering, for the time being, actual structures, I will try to mention typical antiearthquake measures employed by the Central Asia architects.

Let us start with mortars. The major bonding materials were "ganch" and clay. Though the Central Asia architects were aware of lime mortar, they preferred ganch for its strength and plasticity. The ganch was prepared from the local alabaster by firing, subsequent grinding and sifting. Skilled craftsmen preferred ganch of coarse grinding which set slower than finely ground ganch and became most strong in a year. Pure ganch was almost never used as a mortar. Usually, still in the dry state, it was mixed with other components: loess, sand, charcoal, and other unknown materials. All these additions imparted to the ganch mortar the properties builders needed in a given locality. Sand and brick crumb were inert aggregates, while loess was used to retard the setting process and to enhance cementing properties of the mortar. Ash was added to improve the water-resistant properties of the mortar. Clay and charcoal were mixed with ganch to add ductility to the bond. Mortars of different qualities were required for one and the same structure. This was well understood by ancient architects. Varying the composition of additions to ganch, ancient builders imparted the required properties to the mortars. In the mausoleum of sultan Sanjar in Old Merv, the 12th century, the lower tiers of bricks were laid on a ganch with ash and charcoal, the middle part–with brick flour, and the top part–with a ganch and sand. Ancient craftsmen

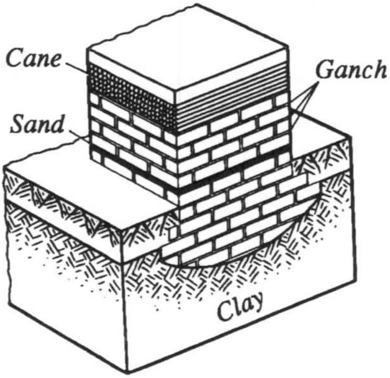


Fig. 91. Typical antiearthquake measures used in Central Asia

were in constant search for improving the mortar that seemed to be perfect already. Finally, they obtained "sheresh" which was a powder of dried and ground roots of plants a small pinch of which per usual ganch batch of 10-12 kg made it resist water and essentially retarded the rate of setting. Most buildings in Central Asia were erected using this strong ganch mortar with improved elastoplastic properties compared to the lime mortar.

The erection of these structures began with digging pits whose bottom was covered to a depth of 60-80 cm with a dense mass of raw pottery clay without admixtures. Such a plastic clay pedding can be seen almost under all architectural monuments built from the 10th to the 17th centuries. Sometimes, the pit bottom was stamped by the hoofs of horses before covering with clay. A foundation of burnt bricks, usually on a clay mortar, was laid on the base prepared in this way (Fig. 91). The foundation foot was slightly curved. This was the first measure against earthquake shocks. The clay pedding with plastic properties absorbed shocks caused by earthquake waves. A curved foundation entered a plastic pedding more easily. To prevent a clay pedding from drying, special measures were taken in the form of fills and pavings. At present various rubber-metal, coursed, antiearthquake shock-absorbers are used instead of such elastoplastic peddings.

After the brick foundation was laid on clay whose thick layers also performed the function of elastic pads, a brick course was laid on a lean loess mortar containing up to 80 per cent of sand. A plinth wall of building was then erected. It was this layer of lean mortar under the whole building that was the next seismic stability measure. A millennium of years later it would be called a sliding band which was made of two strips of stainless steel or plastic. The purpose of sliding bands was to reduce earthquake motions transmitted from the ground to the building. When the earthquake force overcomes the friction force between the band strips, the structure slides, thus decreasing the earthquake load. The less the friction force, the better. By the way, sliding bands of sand are used in China even now, and in Japan a lubricant is placed between the band strips to substantially reduce the earthquake effects.

So, the plinth wall was laid. Before starting to erect the walls, the top surface of the plinth wall was thoroughly levelled with a layer of mortar, laying a cane band over it. The cane band was a uniform course of cane, 8-10 cm thick. The cane was thoroughly laid straw by straw, perpendicular to the wall plane, so that the cane could not be crushed by the bricks of the above wall. Sometimes there were two such bands or none. Their purpose was the same as that of sliding bands and elastic spacers, i.e. to reduce the motion transmitted from the base to the structure during an earthquake. The building base moved in an earthquake, while this motion was almost not conveyed to the building, since due to the cane band the joint between them was ductile. My thought was to show you a present-day analogue of the cane bands. First I wished to name cast-iron balls that provide rolling friction between the building and its foundation, but I understood that it would not do. Should these balls be of tough rubber, it would be alike.

Walls were already erected on a cane band. The structure of the walls was such that they themselves were a seismic-stability measure. Clay could be used as a mortar for the walls.

The walls of survived mausoleum of Fakhr-ad-din Razi, the 12th century, were made of clay and its dome laid on ganch. However, most often the walls were laid on ganch. It is of interest how the walls were erected. At the wall foot the mortar thickness was equal to the brick thickness (5 cm) and decreased with height to become 10-12 mm in the top part. The result was that the ganch volume in the total wall volume was up to 30 per cent, which imparted to the brick wall the elastoplastic properties required by seismic stability. The ganch was also used to lay all elements of joining the walls to the dome and the dome itself. Those were earthquake-proof measures taken by the Central Asia architects to make their buildings resist earthquake shocks. By the way, reinforcing the brick masonry with wood was also widely applied. It is time now to familiarize ourselves with specific edifices to see how the principles of earthquake-proof construction were implemented [35].

Mausoleums, Mosques and Minarets

If some of you are lucky to get to Central Asia and visit some ancient monuments, scrutinize the pattern of their brickwork, and you will see the eighth wonder of the world. I am always astonished at the brick patterns weaved on minarets raised into the sky. A minaret is a tall tower tapering with height. The taper surface of the minaret is decorated with repeated patterns laid of coloured bricks. It seems that with height, these patterns will not align to violate the pattern harmony. But this never happens, and ring after ring, higher and higher you can see a complete pattern. To make sure that this is true, one has to go around the minaret several times. It is worthy of seeing how uniformly and smoothly the walls are joined to arches and domes. Frequently, this intricate structure is built of one-size bricks. A mosque of intricate configuration of the 11th century known as Talkhatan-baba, which is located near the town of Mary, is fully built of standard-size bricks 25 by 25 by 5 cm. According to Pribytkova, the known investigator of the Central Asia architecture, the use of burnt bricks was started in this region in the 8th century, and its shape was dictated by the seismic stability problem to ensure the uniform and monolithic masonry. I would say even more, the brick layout in the masonry, its patterns are dictated not only by aesthetics, but also by the properties that must be imparted to a given section of the wall or dome. There exists a legend that ancient craftsmen burnt a brick so that it rang when struck. More than that, it produced the sound "la". I have a brick with traces of the craftsman's fingers at home, which actually makes a ringing sound when struck. I cannot say whether it is a "la" note, but it obviously is very strong.

Let us start our trip to the country of brick and sun with the city of Samarkand, a city that saw all storms in Central Asia and in whose ancient monuments the history of the building skill of that age was impressed.

In order to fancy how the architecture compositions and structural-spatial and planning concepts of ancient buildings varied with time and how this affected their seismic stability, it would probably be enough to consider a complex of religious structures. The formation of the latter was started in the south of Samarkand, the 11th century, near the imaginary grave of Kusam ibn Abbas (Shakh i Zinda–alive king); its construction was completed in the 15th century. Kusam ibn Abbas, a real and important person, was a cousin of a prophet Muhammad. With the first troops of the Arabs he came to Samarkand in the 7th century and was killed. If we return to the history of construction we are interested in, then analysing the architectural monuments of Shakh-i-Zinda, we can see the evolution of architecture in all Central Asia, of course, with some exceptions.

This evolution of dome structures is shown in Fig. 92. The first one is a proportionally built, moderate-size mausoleum of Khoja Akhmad with a small portal. The dome of this mausoleum is a single-wall type and slightly lancet-shaped. The dome thrust is taken up by the walls reinforced by arches spanning the wall niches. From the standpoint of seismic stability, this mausoleum is O.K. The presence of a portal, however, impairs the centricity of the monument. By the way, the earliest mausoleums were better from the view-point of the structural-spatial and planning concepts obeying the principles of earthquake-resistant construction. In this respect a classical example is the mausoleum of Samanids in Bukhara, the end of the 9th century, whose composition is most simple. It is a low-built cube, 10.8 by 10.8 m in plan, 9.0 m high (Fig. 93) erected on a small brick stage. Like the whole of the mausoleum, the walls, 1.8 m thick, are laid of ganch-bonded

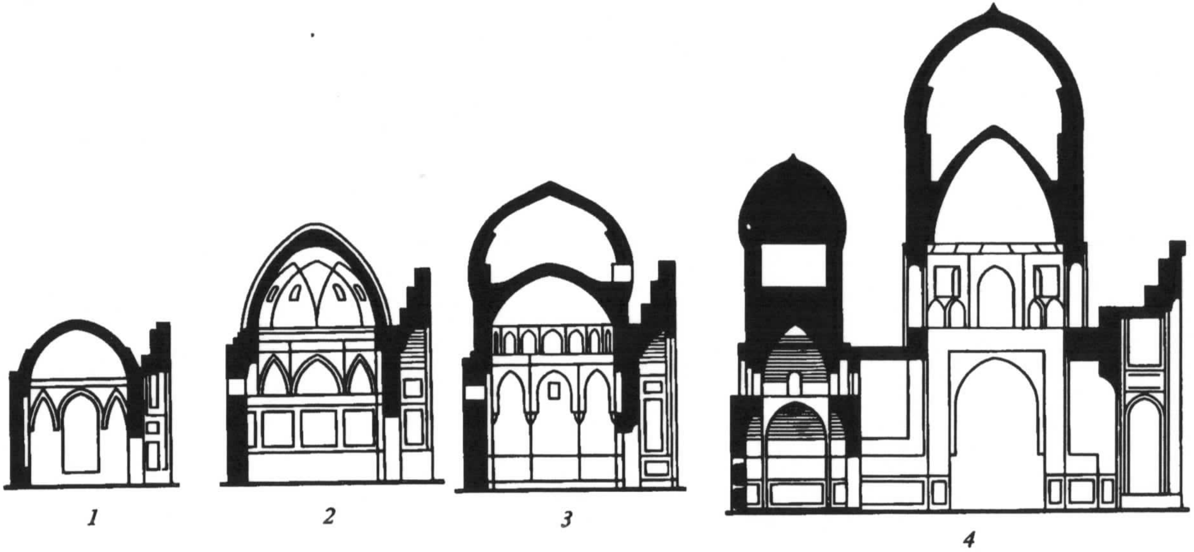


Fig. 92. Evolution of mausoleum dome structures in Central Asia

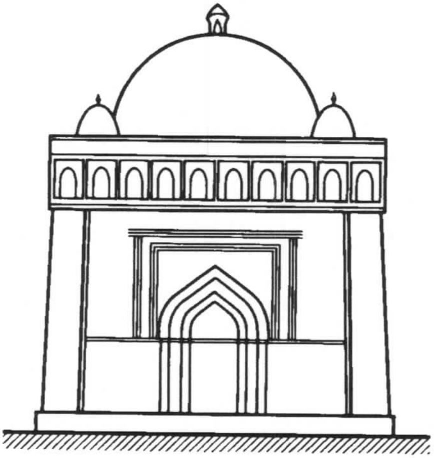


Fig. 93. Mausoleum of Samanids, ideally proportional from the seismic stability viewpoint

bricks. By means of arch-type trompes, the wall square is transferred into an octahedron which is smoothly jointed to a spherical dome. Here you have an example of ideal proportions and dimensions desirable for an earthquake-proof building of rigid structure. This has been proved by the thousand-year history during which this monument exists.

It should be noted that there are many ancient structures of ideal proportions in Central Asia. Their geometrical harmony is in detail discussed in the fundamental work of M.S. Bulatov. As to me, I wish to name one more perfectly proportional mausoleum without portal that has no analogue anywhere in Central Asia. This is the mausoleum of Fakhraddin Razi in Kunya-Urgench, the 12th century, which survived after Urgench was defeated by the Mongols (Fig. 94). The mausoleum stands on a foundation extending at the footing and has outside dimensions of 6.5 by 6.65 m in plan. The dimensions of the internal square room are 3.63 by 3.63 m. The height of the cube slightly tapering upwards is about 6.7 m. The mausoleum cube is vaulted by an internal spherical dome. The external dodecahedral conical dome, laid by the pseudo-dome method, i.e. by corbeling stones, rests on a do-

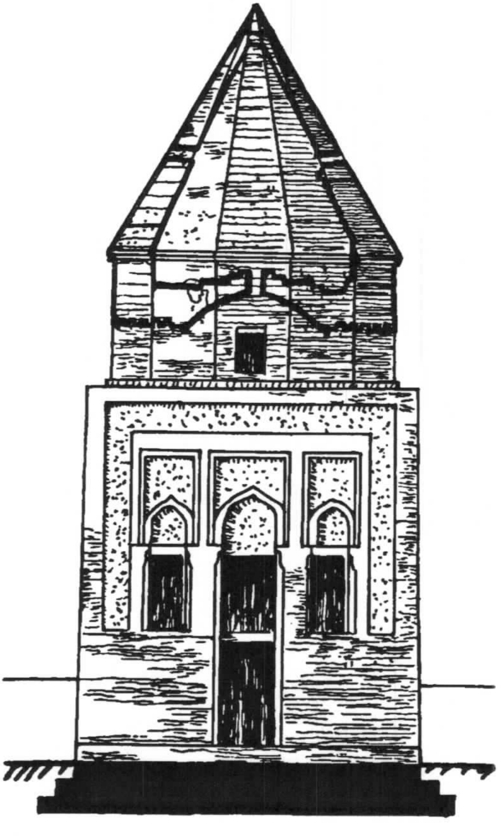


Fig. 94. Smooth geometry of the Fakhraddin Razi mausoleum

decahedral drum smoothly transferring into the walls. This drum houses a bulky internal dome. The outline of this dome is shown in the figure by the dotted line. The external and internal domes together with the drum form a single closed contour, which corresponds to one of the principles of earthquake-resistant construction. The walls of this mausoleum are built on a clay mortar, while the dome masonry is ganch bonded. The result is that the rigid shell of the domes rests on a bulky elastoplastic body that serves as an insulator from ground shaking caused by earthquake waves. This structural scheme is very much like that we saw in the tomb at Halicarnassus.

After the short logical excursion into depths of ages, we shall return to Fig. 92 showing the evolution of domed mausoleums. This evolution started with ancient centric mausoleums, then went over from equally important facades to separating a major facade and decorating it with a splendid, very bulky portal. The portal-dome structures appeared that were no longer centric with equal distribution of masses and rigidity, according to the principles of seismic stability. Figure 92, No. 2, shows this generation of mausoleums, i.e. the mausoleum of Shadi-Mulk-aka, the 14th century. The dome span has been increased, and the dome is supported by rigidity ribs forming the underdome skeleton. The pressure exerted on the ground under the foundation differs from the one under the portal where it is usually greater. This was known to ancient builders, and they increased the depth of the foundation under the portal. It is an evident violation of the seismic-stability principles, since the masses are not equally shared by the structure elements. As a result, the joint between the major mass of the mausoleum and the portal is overloaded, and the failure of the whole building starts at this point. An example is the so-called "mosque in Anau", in fact the mausoleum of sheikh Jemal-ul-Khak-Uadin built in the middle of the 15th century (Fig. 95). The mausoleum situated on a low hill near the city of Ashkhabad is built of rectangular burnt brick of very good quality on a ganch mortar. This did no good, and the destruction of this monument started with separation of the portal and cracks in the dome and ended by complete collapse during the Ashkhabad earthquake in 1948.

The next stage of the evolution of domed structures is represented by the mausoleum of Shirin-bek-aka whose sectional view is shown in Fig. 92 under No. 3. In this case, use is made of a double dome comprising external and internal domes, the external dome being thrustless type. That's where a question arises about the shape of Mohammedan domes. Whether it is associated with religion, or a choice is made of a perfect structural concept. I think both apply. Figure 96 shows the sectional view of a dome in India from which it can be seen that it is as if a balanced sys-

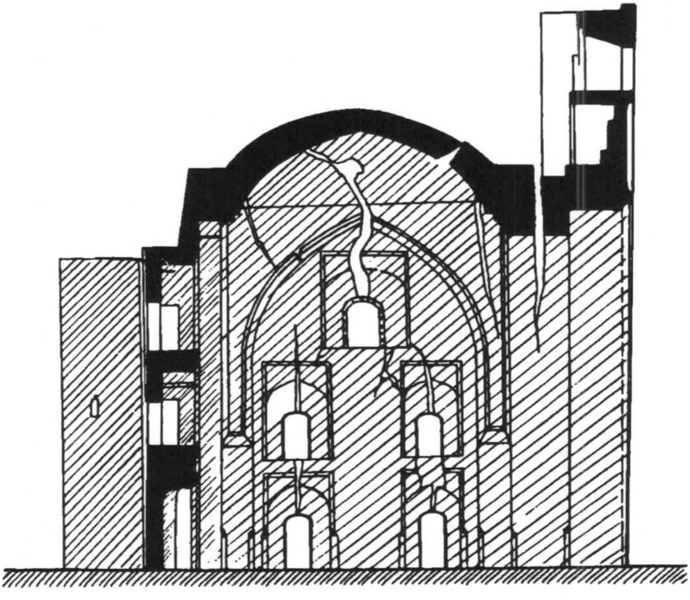


Fig. 95. The last but one stage of mosque failure in Anau

tem. In this case, at least at the center of the dome, each stone is laid so that its inward overlap is balanced by its outside thickening. The efficiency of Roman buildings has already been discussed, but we may say that this applies to all the ancient architecture. The ancient builder did his best to erect strong, reliable, and cost-effective buildings which met the architectural requirements and stood for ages, and he could not yet do otherwise. Recall the lancet Mohammedan arches. They are beautiful from the artistic point of view and reliable—from the structural viewpoint. Hinges formed during an earthquake at the vault head or supports of a lancet arch do not lead to the arch collapse, while a round arch has a greater chance to fail (Fig. 97). The double domes shown in Fig. 92 form a closed uniform contour, which is good from the standpoint of seismic stability.

At the turn of the 14th and 15th centuries new substantial changes occurred in the architecture of religious and memorial

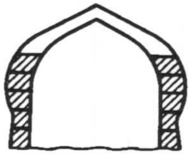


Fig. 96. Thrustless selfbalanced dome

structures. This is associated with the appearance of the empire of Timur with the capital in Samarkand where immense riches were accumulated, to where the best craftsmen arrived from all lands of the empire, and wherein huge armies of unskilled labourers were formed. All this created historical prerequisites under which the evolution of domed structures reached its peak. The evolution ranged from the low-built cubic structures to the splendid, well-proportioned mausoleums with turquoise domes highly raised by drums, which appeared during the age of Timur. The sizes of structures grew larger, the architects became ill with gigantomania, and the towers of minarets went higher and higher. The complex problems of building huge structures called for the development of the construction technology. Enlarged mausoleums, erection of very high, slender minarets, large spans of domes raised very highly, all this contradicted to the principles of earthquake-proof construction. Ancient architects who were well aware of that started fighting for seismic stability of their gigantic structures. The depth of foundations was significantly increased. Normally, foundations were laid at a depth of 4-5 m using stone and special waterproof "cyrov" mortar (lime with ash), which provided a reliable base for heavy portals and high minarets. The wall masonry of burnt bricks on ganch met the new, more strict requirements—it was monolithic, strong and ductile. Serious problems were provoked by an increase in the span of vaults and domes. All domes were made double-shell for uniform distribution of the load produced by a large span dome. A special system of brick ribs was developed, which transmitted the load to the wall and the inner dome. The most important was a system of girth arches that supported the vault and dome drum allowing the creation of large internal halls without substantial increase in the

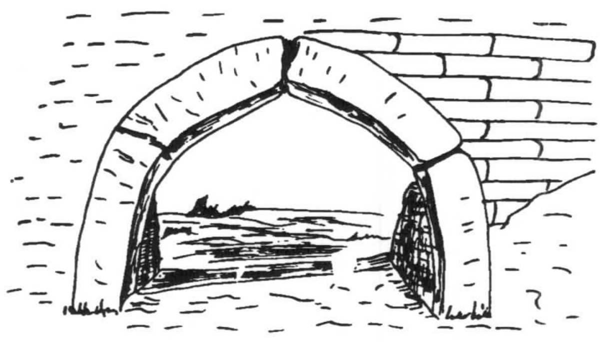


Fig. 97. Seismic stability of lancet arch

diameter. The weight of the whole structure was reduced by this system. Note that the girth arches of Central Asia resemble the double intersecting arches of Armenia, which also support vaults, the last system being much more complicated. There was a perceptible tendency of materially reducing the weight of structures; heavy vaults and domes laid of bricks before are now made as thin-walled structures on ganch.

In the 15th century the composition of structures became more complicated. Along with domes raised highly, which violated one of the seismic-stability principles, two dome mausoleums were built in which burials were made and which had a special room for conducting rituals and ceremonies. Diagram 4 in Fig. 92 is an example of a double-dome mausoleum, the 15th century, ascribed before to Kazy-zade Rumi. The diagram shows that this mausoleum does not at all satisfy the principle of uniform distribution of masses and rigidity. The foundations are laid at different depths, different domes are raised to different height, there is a portal, and the walls differ in thickness, but even in such cases the seismic stability of a building can be ensured by structural measures. This mausoleum still exists.

It follows from the above said that ancient builders were well aware of the danger of gigantomania in the architecture from the standpoint of seismic stability. Enlarged structure dimensions, higher centre of gravity of the structure due to raising the domes, increased spans of arches and domes, plus asymmetry of the multidome mausoleums, all this violated the principles of seismic stability and affected the earthquake resistance of structures involved. We have already discussed structural techniques used to protect the splendid mausoleums of the new generation against earthquakes. Let consider one more mausoleum of that time.

After his brilliant victories over the Gold Horde and guided by political and religious motives, Timur bade his architects to erect a new burial vault of unprecedented magnificence and size in the city of Yasy, now Turkestan, in place of the old burial vault of sheikh Akhmed Yasavi, the 12th century. Timur himself participated in the discussion of the dimensions of the structure and its configuration. The construction was started in 1497 and was conducted at a very rapid pace, but in 1505 Timur began a campaign against China and suddenly died. This stopped the construction which is not yet completed.

In addition to the burial vault of Akhmed Yasavi, the complex includes a mosque, a madrasah with a library, and a khalimkhana where food was distributed among piligrims twice a week, and so on. The mausoleum-mosque is an enormous portal-domed building with one plane of symmetry. Figure 98 shows the general view, longitudinal cross-section, and a plan of this structure. Its dimensions in plan are 46.5 by 65.5 m, its portal is 50 m wide, the span of the portal is 18.2 m, the diameter of the largest brick dome from those survived in Central Asia is also 18.2 m. The thickness of the outside walls runs up to 2.0 m. The thickness of the inner walls supporting the central dome is up to 3 m. We shall not become absorbed in the eventful history of this outstanding monument of architecture which underwent plunder by the Gold Horde of khan Tokhtamysh and Stalin's concentration camps at our time. Let's deal with its seismic stability.

The mystery of this structure starts with the foundation. It remains an enigma why gifted builders of that splendid structure treated its foundation so lightmindedly. Usually, the foundations built at the time of Timur feature excessive strength and weight. They are laid of large stones on a lime mortar with ash, which makes them waterproof and strong. Under this mausoleum edifice, however, there is no solid foundation. A few courses of brick

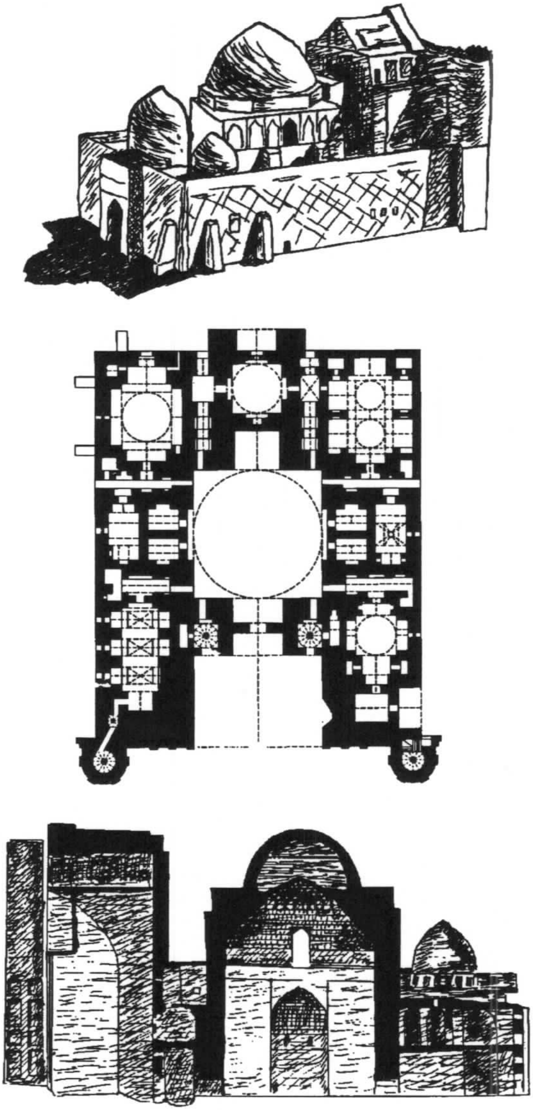


Fig. 98. General view, plan and section view of the Akhmed Yasavi mausoleum

careless masonry are laid under its walls, only to a depth of 25-30 cm, the pit under the heavy portal is filled of large pebble mixed with ground. The cause of erecting the ensemble of Akhmed Yasavi on weak foundations is very simple and can be understood by us. Sovereign Timur set off to meet his bride Gukel-Khanym, but had to deviate from his pleasant itinerary to found a mausoleum which was not to the point. Everything was done in a hurry. The loyal subjects did their utmost to please their ruler and to show everything at its best. There was no time to lay a good foundation. They wished to erect the walls as rapidly as possible to have them seen by Timur. In short, the ancient builder made the foundation carelessly owing to circumstances beyond his control. Fortunately, this monument was not subjected to severe earthquakes up till now. However, the poor foundation was the major cause of its destruction due to unequal settlements. Much injury was done to the mausoleum base in 1846 by the Kokand troops. In order to captivate Kanatshah, the ruler of Turkistan, who ensconced himself in the mausoleum, they used a system of dams to floor it, and the mausoleum foundation remained flooded for a long period of time.

However, the major secret measure that saved the mausoleum of Akhmed Yasavi with poor foundations and under conditions of increased seismicity and previous severe moistening of loess settling grounds consists in that the mausoleum is split into eight independent spatial blocks. Structurally, the antiearthquake joints are shaped like four through two-storey corridors (Fig. 98), which allow parts of the building to move during an earthquake, or, in case of unequal settlements, regardless of each other, thus causing no overstresses in this large-size building. The cross-section of the mausoleum demonstrates that the major dome rests on the internal walls ensuring its individual support. This sectioning into separate blocks helped ancient architects to overcome gigantomania.

Though sheikhs always lived around the mausoleum-mosque and supervised the established customs and performed rituals, its construction is still uncompleted. For example, the main portal neither has two minarets proposed by Timur, nor the facing. Admittedly, Abdulla-khan, the ruler of Bukhara, tried to complete the construction of the mausoleum at the end of the 16th century.

At his time, the main arch of the portal was fully spanned and something more was done. It's a pity, he did not order to erect the minarets that ought to add load to the portal, thus helping it take up thrust caused by the main arch.

We have talked about the mausoleum of Akhmed Yasavi to tell the reader about the sectioning of large buildings into separate blocks, which was known to ancient architects. In passing, something curious is to be discussed. An arch of burnt bricks laid on an unknown highly ductile tarry mortar was found in it. This mortar was a mixture of an unknown tar with sand and loess. When applied to the brick in a hot state, the mortar formed a very strong bond, imparting high strength and improved elastoplastic properties to the masonry. It is clear that this mortar only, if used in wall masonry and in such important structures as arches and domes, makes them exclusively durable and antiearthquake. There is no doubt that this new unknown tarry mortar was obtained as a result of profound creative research, the task being set clearly. Dear reader, if you deal with the earthquake-resistant construction, you must confess that you were not aware of the antiearthquake techniques of ancient architects until you happened to encounter this publication. Now you are certain that there is much interesting and wise in the experience of ancient builders that you must know. There are two more examples related to the creative search of ancient builders.

The minaret of Kalyan towers that rises over the city of Bukhara will soon see its 900th anniversary. The minarets are most outstanding creations of Central Asia. Their slender turrets can be well seen against the background of the blue sky. One can hardly believe that they are built of brittle bricks. Moreover, frequently they stand alone, without a mosque attached to them. Their mosques, more rigid and solid, and more strong, as it might seem, were destroyed by earthquakes long ago, while these slender and flexible structures of brittle bricks survived. Minarets at the cathedral mosque in the city of Bukhara were erected twice, and each time they collapsed. Finally, the third attempt was a success. In 1127-1129 the minaret of Kalyan (Fig. 99) was built on a very strong and deep foundation laid at a depth of 10.0 m, according to some publications, and, according to other works, 13.0 m-deep bore pit did not reach the rock base. The minaret was laid of burnt

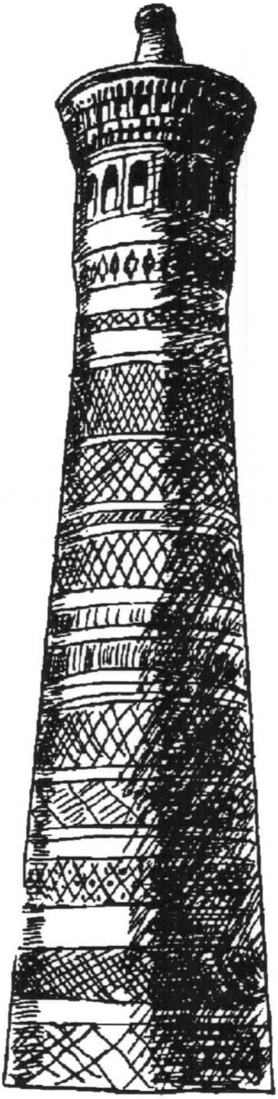


Fig. 99. Minaret of Kalyan after 900 years of natural selection

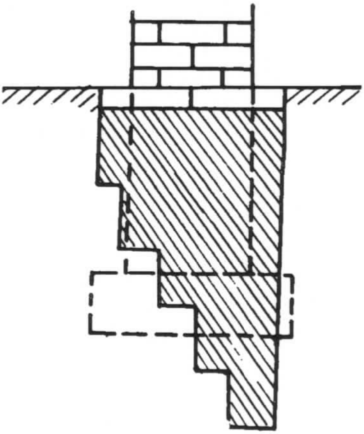


Fig. 100. Unconventional foundation narrowing with depth

bricks ganch-bonded. Its present height is 46.0 m. It is assumed that another turret stood above the lantern topping the minaret, which collapsed during an earthquake. The minaret diameter near the octahedral high socle is 9.0 m. The intricate roofing above the lantern is supported by 16 lancet arches forming the same number of openings through which in past times sixteen muezzins simultaneously called the hour of daily prayers. Nowadays the minaret of Kalyan cannot be called very slender, its taper shape rapidly narrowing with height looks low-built. The natural selection has shown that the minaret of Kalyan can resist earthquakes—it stands, while many other minarets collapsed; only a few have survived. It is just these few survived architectural monuments we are interested in. They give information on the required depth of foundations, configuration of earthquake-proof buildings, and, finally, dynamic characteristics desirable for buildings in a given seismically dangerous zone. In addition, old scars on their walls inform us about bygone earthquakes.

Now we shall talk about the unique foundation of the famous mausoleum of sultan Sanjar in Old Merv. The foundation of this mausoleum does not extend with depth, as usual. In this case, it is the other way round, the foundation narrows stepwise with depth (Fig. 100). The traditional shape of foundation is shown by dashed line. The whole of the stepped foundation is embedded in a body of soft clay. What is it, a mistake or a brilliant surmise? To my mind, it is the latter. Imagine that shipbuilders would build ships with flat blunt bows. Would it be easy for such blunt-bow ships to cleave through sea waves and what wave impacts would be exerted on them? This is how our foundations extending with depth are exposed to direct rigid blows of earthquake waves. The stepped foundations narrowing with depth and placed in a huge pit filled with soft clay, as in the mausoleum of Sanjar, are for sure to split, reflect and scatter the earthquake waves.

I want to repeat that ancient builders never placed their structures directly on the natural rock. The early monumental structures of Khoresm built in the 3rd-8th centuries already stood directly on sand pillows formed by sand filling and levelling the nonuniform rocky grounds. A mausoleum built on a steep slope of the mountain Takht-i-Suleiman near the town of Osh stands in a pit made in the rock and filled with sand. The mausoleum of Chupan-Ata, near Samarkand, is structurally designed in the same way. A pit is made in rocky ground and filled with loess loam to form a pillow for the mausoleum. As you see, seismic-stability measures were taken while preparing the ground base.

One more problem important from the standpoint of seismic stability we should dwell upon concerns the joints between the walls and domes. As a rule, this problem was well tackled in Central Asia. In the middle ages, no round buildings were erected in this region, they had to conjugate a square to a circle. The typical approach was used in Central Asia. Arched trompes were employed to span the square corners. These trompes supported an octahedron which was then joined with the dome. This conjugation is shown in Fig. 101, an example being one of the mausoleums built in the 11th century. You see how the walls are lightened by niches spanned by lancet arches. Laid in the piers between the arches are ribs of rigidity shaped like columns embedded in the wall. A new system of arches forming the octahedron is located above. Next goes the dome which was improved, lightened and reinforced in the course of ages.

There is one more curious moment. Note how widely used by ancient architects were curvilinear structures, such as arches,

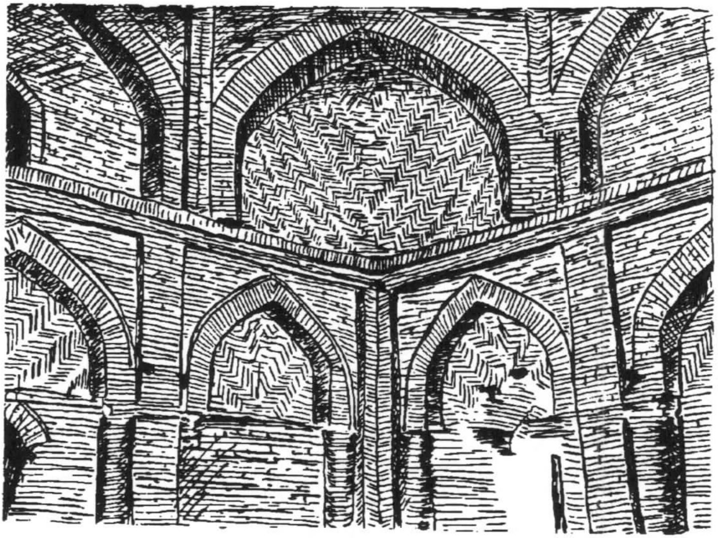


Fig. 101. Smooth conjugation of a dome with building walls

vaults, domes. All these well built structures demonstrated their durability and reliability, decorating monumental structures at the same time. And how rarely these structures are used at present. Everything is simplified to the utmost, and our buildings are plain and flat. Now it's time to talk about wood as a building material that agrees with the seismic stability requirements [35-43].

Seismic Stability of Wooden Structures

Of all the traditional constructional materials the light, strong and elastic wood meets the seismic stability requirements best of all. Today there are good substitutes for the wood. These are plastics still lighter and stronger than wood and available in any shape, and also air structures based on the conventional air. Nevertheless, some words should be said about the ancient wooden structures.

One of the most ancient structures based on wood, which is widely used up till now, mainly in the residential construction of

Egypt, India, in the Caucasus, and China, is represented by a building having a timber framework filled with clay mixed with straw or animals' wool. With a well-made framework and a light roof, these buildings satisfy all the seismic stability requirements and stand well to most severe earthquakes. Generally, ancient builders were good judges of wood, and it was not for nothing that wood reinforcement of brick and stone masonry was mentioned many times.

Maybe, you noticed that, describing the architectural monuments of Central Asia, I never mentioned stone columns. What is the matter? Let us look into it in detail. No stone columns remained in the survived structures, though it is known that attempts were made to erect such columns. In the cathedral mosque of Timur named Bibi-Khanym whose dimensions were gigantic, 83 by 62 m, use was made of 400 marble columns, more than 4.0 m in height. This mosque had a misfortune: it collapsed during an earthquake. There were, perhaps, other examples of misusing stone columns. Anyway, ancient architects did not repose trust in such columns.

Taking into account seismic danger of the region, the stone columns could not be made sufficiently flexible, as was required. Brick pillars did find their application as intermediate supports, since they could be made flexible by the known methods, utilizing mortars. Brick pillars were of considerable thickness, about 80 cm, the masonry being laid on thick courses of a ganch mortar. Such pillars were particularly widely used early in the 11th century. Later on, these pillars were rejected. A comparable brick pillar was mentioned in the sity of Mesopotamia and shown in Fig. 17.

But widely used in Central Asia were, are and will be traditional light wooden columns that are structurally very perfect (Fig. 102*a*). The figure shows that this column, first of all, has a beautiful fretted base widening towards its foot. The top of the stone base has a socket to receive the lower tenon of light wooden column tapering with height. The column top also has a tenon inserted into a seat provided in the bolster which, in turn, has tenons as its ends that fit seats made in the ceiling beams. The result is as follows. The column is hinged at both ends. Therefore, it works only in compression without bending, thus being loaded

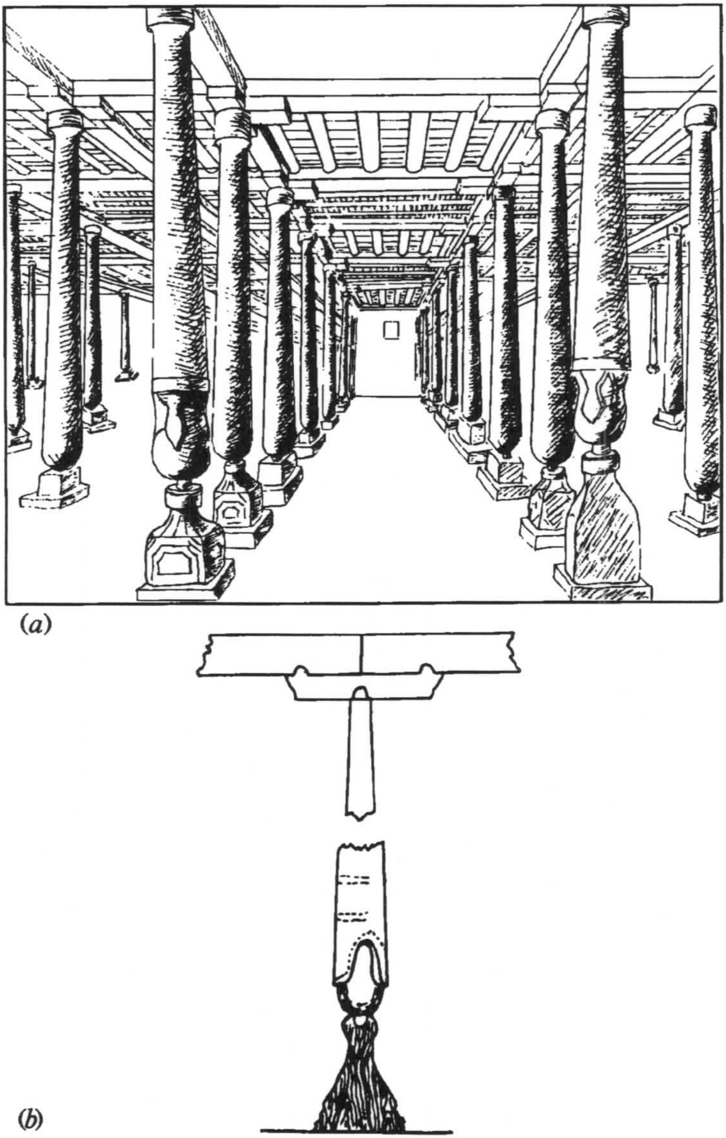


Fig. 102. Juma-mosque on multihinge columns, design of one of such columns

uniformly. Next, the use of the bolster reduces the column-to-column span to substantially decrease the maximum bending momentum of the load-bearing beams. Besides, the use of tenons prevents the assembly from coming loose and its elements from misfitting each other under heavy shaking that takes place in an earthquake. Finally, the most important is the fact that the double-hinged columns will convey no motions caused by the earthquake shocks to the ceiling from the ground base. The ceiling will receive horizontal motions only from the walls which themselves must take up this horizontal load. The remarkable column in question is widely used in the Central Asia construction. It serves to support light wooden ceilings above widely spread traditional open terraces, ayvans. The same column was used in the monumental construction. The famous Juma-mosque in the town of Khiva (Fig. 102*b*) was founded in the 10th century. It is 55 by 46 m in plan and up to 5 m high. The mosque accommodated all the male population of the town during the divine services on Fridays. The flat ceiling of the Juma-mosque is supported by 212 columns of the above design. Four of these columns are ancient and feature carving of particular beauty; these columns date back to the 10-11th century. As you see, the Juma-mosque has proved the seismic stability of its structure by a thousand-year existence. The structure is as simple as a masterpiece of genius can be. It has no rigid units at all: a light ductile wooden ceiling, all joints have hinges, the low horizontal loads are conveyed to the walls located along the perimeter.

Now let us turn our mind a few centuries forward, to the time when the Russians, very skilled in the wooden construction, came to Central Asia. Let us start with a most simple and most popular element of the wooden architecture, i.e. with the Russian izba. After the Russians pioneered Siberia and Far East, the Russian izba appeared in the Transbaikal region, Altai area, Kazakhstan, the regions of high seismicity, wherein it stood best to earthquake shocks, though initially its design had not been adapted to earthquake resistance, like, for instance, the Japanese pagoda.

Recall how the conventional Russian izba is constructed. It is built on the basis of the so-called log framework which is assembled of horizontally laid, thoroughly fitted to each other logs. Each log has a notch cut underneath and a projection on its top through the whole of its length. Besides, the ends of each log at the joints to the transverse walls have cross cuts. The result is that each log laid in the framework is engaged with the log under it and the transverse wall logs to form a single, nondetachable system out of which none of the logs can be knocked off without destroying the whole wall. This framework can deform in any direction through logs shifting relative to each other along the notch. Naturally, this system provides good damping, its material is light, strong and ductile. The structure features the symmetry property. The fact that Russian izbas (log houses) provide high resistance to earthquake shocks has been proved by many earthquakes. During the earthquake in Irkutsk, November 7, 1958, magnitude 8-9, the log houses suffered least: only fissures occurred in the corners of some log houses. During the earthquake in the city of Vernyi, 1910, whose magnitude was above 9, the log houses with a good stone foundation under the whole house did not suffer at all. We shall still return to this earthquake.

Now, imagine the following unreal situation. There is a world competition held for the most earthquake-proof structure for all times. Each participant is to present any design of an antiearthquake building of the past, present, or future. Without thinking long, I would present the Russian izba hoping to win the competition, at least to be the first, but one, if the Japanese pagoda were the winner. Besides, I would propose to slightly improve the Russian izba in order to prevent its logs from coming out of the notches in very severe shocks. I would do it by threading metallic rods at some points, including corners, through all the framework logs, securing rods at the top and bottom. It is this, but far more complicated than the Russian izba, structure of wood reinforced by metal that I want to tell you about now.

We shall speak of the Sofia cathedral church built in the city of Vernyi, now Alma-Ata. It was founded in 1904 and hallowed already in 1907. This splendid edifice standing in the center of Alma-Ata is studied little and is not much written about. I got to know this cathedral church from the book *Custodian of Antiquities* (*Khranitel drevnostey*) by Yu. Dombrovsky who is now widely published. In this work of art Dombrovsky described in detail the arrival at Alma-Ata in the thirties, his meeting with the cathedral church and talk with the church watchman, an old Kazakh. He told Dombrovsky about the Russian military engineer, A.P. Zenkov, who, as it were, built this cathedral church without a nail, using Tien Shan white spruce, and reconstructed the city of Vernyi after a very severe earthquake, 1887. Dombrobsky was exiled to Alma-Ata and worked in this cathedral church where a museum of ethnography was then situated. Dombrovsky tells in his work about the seismic stability of the cathedral church and other wooden buildings erected by Zenkov. I was interested much in these stories, but something gave rise to doubts. For example, he did not mention the great Russian scientist I.V. Mushketov who was just busy with the earthquake of 1887 and participated in writing the *Measures Specified by the Technico-Construction Committee to Be Applied in the Urban Settlements of the Semirechensk Region.*This was one of the first specifications worked out in Russia that gave recommendations on construction of earthquake-proof buildings. Being interested in this story related to the cathedral church, I tried to find out something to tell you about further.

The instructions of tsar Nicholas I for construction of a fortified settlement called Vernyi was signed in February, 1854 in Semirech'e (Seven-river area). In 1855 a temporary fortification was constructed, and the town started growing rapidly. Perhaps, in order to warn future builders and citizens of the town about threatening catastrophes, two very severe earthquakes took place at the beginning of its history.

The first severe earthquake in the city of Vernyi occurred in 1887. In addition to some preliminary minute shocks that made citizens move outdoors, two more heavy shocks took place at an interval of 10 min. Most damage was caused to the buildings of different masonry, in particular, those of air-dried bricks, and a brick church collapsed. In short, 1800 of such buildings were destroyed. On the other hand, 800 wooden buildings found in the city survived; ruined were only their brick chimneys and stoves. It is easy to conclude that the wooden buildings are more resistant to earthquakes than brick buildings. Published in 1889 were the above *Measures...* that recommended to erect, as a rule, wooden buildings on a stone foundation with a basement under the whole structure and reinforcement of the corners by vertical beams. Recall the vertical rods to be inserted in the corners of the Russian izba to make it most resistant to earthquakes. After that earthquake the town was reconstructed in the wooden version.

The next, more severe, earthquake took place in 1910. The ground displacement in the town of Pulkovo, near St. Petersburg, was up to 4 mm. In the course of that earthquake none of the wooden structures collapsed, including our large cathedral church completed by that time. Again, only the brick stoves were destroyed. People and cattle were killed only in mountains, on pastures, due to landslides. The fact that the town survived could not be due only to one person, even as outstanding as Zenkov. Now we already know that all depends upon the system. There are many skilled builders in Armenia known for its traditional earthquake-proof construction, but the towns of Leninakan and Spitak turned into ruins in 1988 during the earthquake.

Like the case was with other towns in Central Asia and Siberia, here in the town of Vernyi a galaxy of excellent military engineers were engaged in the construction and reconstruction of the town.

I was lucky to get acquainted with the cathedral church in the autumn of 1989, when a museum was made a concert hall. After entering the park, I saw a bright, showing the colours of rainbow, many-headed structure in a pseudo-Russian style that was in fashion at the end of the past century. I entered the church, and a vast internal space opened up before me. It was uniformly and brightly lighted through the wide windows of the underdome drums. From the floor I saw improbably narrow piers between these windows. A thought struck me that the piers must be strong enough to support the dome during an earthquake. I asked a young, nice employee of that institution about the structure of this cathedral church. To satisfy my curiosity, she exactly retold me the same related to Dombrovsky by the old Kazakh more than 50 years ago. She repeated the many-year legend that the cathedral church had been built by Zenkov without a single nail and that it stood on a concrete slab and a sand pillow. Old legends die hard! I listened to the story of that woman with great attention and sincere gratitude, though I knew already that there were not only nails in that wooden cathedral church but whole rails. I was grateful to her, first, for not going on with another, less known legend saying that during the earthquake in 1910 a large fissure formed on the ground surface where a man could descend. This fissure ran directly towards the temple, but took fright at the holy site, went around it, and returned to its way in the same direction. How many talks were then caused by this phenomenon about the sanctity of the site! The only cause was the following. The foundation of the temple was made strong in the form of a single monolithic slab. Second, that woman (a guide) helped me obtain the true information, in particular about the design of the cathedral church. To follow her advice, I entered the church through the back entrance. There I found and got to know a very interesting man, V.N. Proskurin, who told me much of interest about the cathedral church, the town of Vernyi, and about Zenkov. Now I am going to relate to you the results of my investigations.

First, I got to know historically that there lived two Zenkovs, the father and his son. Our A.P. Zenkov was the son born in 1863. In 1887, when an earthquake took place, he lived in St. Petersburg and attempted to enter the Military Academy, which he did in 1889. Therefore, he could not write any instructions for the reconstruction of Vernyi after the earthquake of 1887. His father, however, P.M. Zenkov, an educated man and skilled architect took part in the development of the general layout of Vernyi. He was elected the first mayor of Vernyi in 1877 and ought to participate in working out the appropriate directions. His son, A.P. Zenkov, arrived at the city only in 1899 and headed construction department in 1900. By that time the city had been reconstructed, but continued to extend with account for the earthquake danger; A.P. Zenkov took an active part in this work. Under his supervision a number of remarkable wooden buildings were erected, including the cathedral church. As a talented engineer, he might make corrections to the designs involved, taking into consideration the high seismicity of the area. The decision to erect a wooden cathedral church in place of the brick church that collapsed in 1887 had been taken before. Now it is high time to speak of the cathedral church design. I will relate to you what I have found out and what may be guessed at.

Fig. 103. Multidome wooden cathedral church

As to the height of the cathedral church, there are different versions. According to some publications, it is 56 m and 54 m, and even 59 m. I am scrutinizing the cross-sectional drawing of the cathedral church. It can be well read that the maximum height of the cross top point of the main dome is 39.63 m, that of the cross on the bell-tower, 44.2 m. The top of the base stone slab is 0.55 m. As you see, it is far from 50 m, but for a wooden structure the height of 40 m is fairly great (Fig. 103).

The gable rafter-type roof of the cathedral church is decorated by five domes having bulbs and crosses raised on low-built octahedral drums with wide rectangular windows. The diameter of the central large dome is about 13.0 m, that of the four small corner domes, 6.5 m. There is a rectangular (in plan) bell tower erected axially above the main entrance. All these domed structures are combined into a single system by the spatial skeleton of the roof, which, in turn, is connected to and supported by the walls and the skeleton of the building. The timber sets, closed building skeletons, and roof rafters, all these are made of the Tien

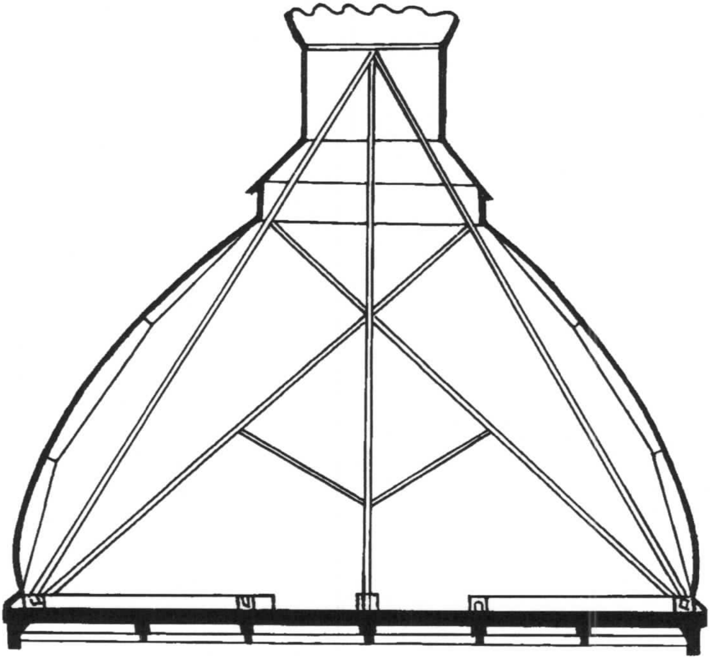


Fig. 104. Thrustless wooden dome

Shan white spruce. Now let us have some talk about the design of individual elements of the cathedral church.

Practically, the light spheric wooden domes with an internal skeleton are made thrustless (Fig. 104), since their total thrust is taken up by the flat coffer-type ceiling. The latter is made at the foot of the dome from heavy-duty beams squarely intersecting each other. These ceilings and their structure are seen from beneath, from the internal halls of the cathedral church. The dome and the coffer-type ceiling form a single closed spatial system. This sufficiently light shell rests on the drum and is connected through the window tiers to the roof. I could not find out the design of the dome drum tiers, and we shall attempt to guess it through the known design of the bell tower: both are made by the same builder.

The base of the bell tower is in the form of a framework made up of the horizontal timber sets, exactly as in Russian izbas, and the resultant framework is fairly high. During an earthquake the high bell tower undergoes bending moments, and the framework that poorly stands to tension will not be able to support the marquee of the bell tower. Therefore, use must be made of auxiliary vertical ties. This is what the architect of the cathedral church did by implementing even three kinds of vertical ties. First of all, the facing of thick boards was fastened to the timber on the outside. Next, since the twelve window apertures affected the strength of the walls, they were reinforced by sixteen couples of heavy-duty timbers running through all height of the bell tower, in the corners and the tiers. This was the second kind of the vertical ties. Then the third unusual, perhaps the main, kind of vertical ties was introduced. The log framework was threaded by eight vertical studs that involved the entire log framework of the bell tower, the high pyramidal roof inclusive, and tied them to the top log sets and the skeleton of the building. These are the seismic-stability improvements which the Russian izba lacks to become a building most resistant to earthquake shocks all over the world and at all times. With the above vertical ties, the bell tower cannot be torn up into pieces or off the closed structure of the building even in case of very severe earthquake, which was proved by the earthquake of 1910. To my mind, it's beyond doubt that the design of underdome lanterns should be exactly the same, and the dome shells are fastened to the frame of the building by the metallic studs. In any case, during the earthquake in 1910, the domes were drastically shaken, which was indicated by their bent crosses, though the domes were not damaged. It would be wise to secure the walls of the building and its skeleton in exactly the same manner, but I could not find out whether it had been done.

Now a few words must be said about the foundation. The cathedral church edifice stands on a foundation slab laid of quarry-stone on a lime mortar. The slab is faced with granite. The plinth wall of the building is also of granite. Structurally, it is like Japanese pagodas: a wooden structure stands on a stone slab, except for one curious element, i.e. the foundation is surrounded by a circular underground gallery. The purpose of this gallery is to stop the surface earthquake waves. The house of Zenkov is known to be surrounded by a ditch as well to improve its seismic stability. This proved effective, because his house was shaken less than others during an earthquake. Exactly the same antiearthquake measure was taken in the cathedral church. What was its origin? I think, it was not devised by Zenkov but originated from traditions of Central Asia. As an analogue, I recall an example of another time and from another distant continent. The most ancient and largest Mayan city, Tikal (the 6th century B.C.—the 6th century A.D.) was situated on the peninsula of Yucatan in North America. This peninsula is known for high seismic activity. In this case we are interested in the fact that the excavated central part of the city consists of nine large groups of buildings situated on man-made hills that are separated by deep hollows. What are these hollows for? Maybe, they represent a seismic-stability measure, rather than strategical considerations. During an earthquake, the surface layer of the ground thickness is shaken most. The shaking intensity rapidly diminishes with depth. When seismic waves encounter trenches and ditches, they are reflected with the result that a building surrounded by a trench stands, as it were, in a calm zone. In short, the gallery around the foundation of the cathedral church is also a seismic-stability measure. The outstanding earthquake resistance of the cathedral church in the city of Vernyi was ensured by the set of the above antiearthquake measures. All principles of earthquake-proof construction mentioned above were implemented in this edifice, but for one exception: there were many towering domed structures. However, adequate measures were taken to compensate for this disadvantage. The domes were well tied to the skeleton of the building itself.

An example showing that a whole group of outstanding military engineers worked in Vernyi is as follows. An earthquake-resistant building, not less unique than the cathedral church, seems regretfully to cease its existence in 1991. This one-storey brick building with a wooden framework stood to both severe earthquakes of 1887 and 1910. Most probably, this building was designed by M.A. Antonov, the head of the Semirechensk Engineering Division. The building housed the Pushkin school for ladies and then a musical school.

The design of this edifice is as follows (Fig. 105). Thick wooden beams, 25 × 18 cm in cross-section, are laid crosswise the

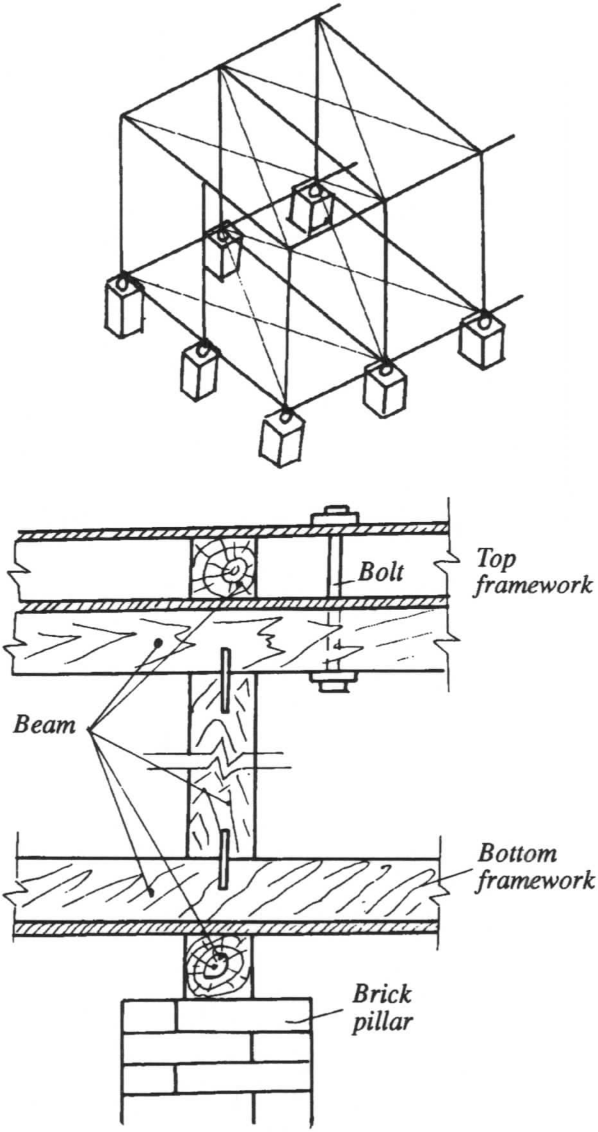


Fig. 105. Seismically insulated brick building, the 19th century

building on high brick pillars. Laid longwise the building on these transverse beams to tie them together are flooring boards. In order to reinforce the boards, wooden beams are laid in the same direction. All these elements are fastened by nails, bolts and cramps. As a result, the bottom framework of the building is formed. Vertical beams are fastened to the bottom disk. Another disk made of transverse and longitudinal beams and boards and supported by the vertical beams is laid at the top of the building. The result is a fairly ductile framework comprising the two disks connected by the vertical beams. Next laid are brick walls tied together and supported by this wooden framework.

The structure is well thought out from the standpoint of seismic stability. Note the high supporting brick pillars bonded by a strong mortar, which form a real earthquake-resistant system. These pillars can turn in any direction not to convey (to the building) motions occurring during an earthquake. These pillars can turn during an earthquake as asynchronously as various points of the ground move. Being thoroughly reinforced by a powerful wooden framework, the building itself features all antiearthquake properties: ductility, strength, uniformity, closed contours. Even the Γ-shape (in plan) did not affect the seismic stability of the building.

After the usual brief survey of the architectural monuments of Central Asia, we shall set off further to the East [35, 44-47].

Japan, China, India, And South-East Asia

In this chapter, dealing at once with so vast an area of the world containing great variety of countries, customs, construction methods, geographic conditions, I am not going to make any historic or economic analysis of the causes of using either structural techniques. I will directly list the structures we are interested in and analyse them from the seismic-stability viewpoint.

The inhabitants of Japan, whose territory features high seismic activity, got to know such an unexpected and formidable phenomenon as an earthquake from the prehistoric times. Knowing very well that light, elastic and strong wood was then an ideal material for the antiearthquake construction, Japanese architects built everything of wood till the 16th-17th centuries.

In order to preserve remarkable architectural monuments, an excellent custom was introduced in Japan in very ancient times to reconstruct anew the wooden temple structures every 20 years, duplicating every minute detail. This time interval was not always adhered to. Nevertheless, copying was made no less accurate to allow us today to study the complete structure of very ancient architectural monuments in very good condition.

Let us consider one of the most ancient wooden architectural monuments of Japan. This is a rectangular (in plan) shrine named Soden (Fig. 106), which is included in the temple complex Ise-naiku devoted to the Sun goddes—Amaterasu-omi-kami, the 3rd century A.D. It is this most ancient construction that shows well the principal structural difference between the Japanese wooden

Fig. 106. Structural perfection of the shrine of Soden

structures and Russian izbas. Japanese structures are based on poles one end of which is vertically dug in the ground. The remaining structure is threaded on these poles. With the Russian izba (log house) all is turned through 90 degrees, the logs are laid horizontally and tied vertically and horizontally. The ties feature high ductility. The logs can slide along the notches, relative to each other, with an increased coefficient of damping. The only disadvantage is that the vertical ties do not work in tension. Hence, in case of earthquake shocks, the logs can slip off one another. To avoid this, use should be made of additional vertical compression, or at least fastening, which was done in seismically dangerous areas.

In the Soden shrine the vertical pole-columns are connected by transverse and longitudinal ties into a single spatial skeleton. Everything is done in compliance with the seismic stability principles. Besides, as shown in the figure, there are two heavy posts arranged along the main axis of the structure outside the building, which support a very heavy longitudinal ridge squared beam. The two posts and the beam resting on them form a very strong inverted-U frame. The latter is coupled with the spatial skeleton of the structure, thus supporting it and enhancing its resistance to earthquakes. The frame and the skeleton, probably, differ in rigidity, the frame being more rigid. This combination of elements with different rigidity into a single structural system is typical for the earthquake-proof construction of early Japan. Further an example will be presented of an antiearthquake structure comprising two systems of different rigidity. This was not yet encountered by us. Note one more typical element of seismic stability in the Soden shrine, which was utilized not only in Japan, but in many countries of South-East Asia. The shrine is well raised above the ground by poles one end of which is dug in the ground, while the other end is tied to the skeleton. These very poles perform the function of seismic insulators. At the ground level the poles are not coupled to each other, and, thus, can move regardless of each other in accordance with the intricate chaotic motions of the ground during an earthquake. Besides, the poles feature some flexibility and somewhat dampen shocks caused by the underground element. At the shrine floor there is a common linkage, including the round-about terrace where the damped motions conveyed from each support are summarized and averaged out. The light roofing is made of thoroughly laid and brushed straw. The workmanship of the superreliable Japanese who made the joints between the structure elements will not be discussed here. As you see, this structure actually meets all principles of earthquake-proof construction.

There is one more example of a wooden structure raised on poles. By horizontally laid logs it resembles the Russian izba, except that there are no notches and the wall logs are not locked to each other. According to their purpose, the logs are very accurately fitted to each other. In dry weather the wood logs dry and the interior is well aired, while in wet weather the logs swell and prevent the inflow of damp air. This is the treasure of Cesoin situated in the ancient capital of Japan, Nara, and built by emperor Cemu in 752 (Fig.107). The rectangular (in plan) building rests on 40 wooden columns, 2.7 m high, reinforced by iron hoops. The columns support beams forming a crosswise system of bracing as can be seen in the figure. The walls of the treasury building support

Fig. 107. The earthquake-resistant temple Cesoin

a gable roof and form a framework assembled of triple-edged beams. Cesoin is divided into three parts by internal partitions made of logs, which connect the longitudinal walls. During an earthquake, the work of this structure is ideally simple. The supporting columns dug in the ground move independently. The crosswise system of beams connecting the column top ends and the building itself are so flexible and ductile that can move and breathe without overstress and destruction, like the tops of the relatively flexible columns do.

There is another, still more unique example. In 621 Buddhism was accepted officially and became the dominant religion in Japan, but already in 577, the first specialists in building the Buddhistic temples arrived at Japan from the state of Pyakche situated on the Korean peninsula. Further, in Japan wide use was made of structures and their parts inherent in Chinese architecture, as well as the general composition of temple complexes. From this time wide application in Japan was found by wooden pagodas in the form of tower structures, up to 30 and even 50 m. All those pagodas were built, following one and the same principle that was shaped for centuries (Fig. 108), though they had some external distinguishing features. The structural system was composed of a few square (in plan) storeys of diminishing (with height) size that formed a skeleton with corbeled cornices. The storeys had a pent

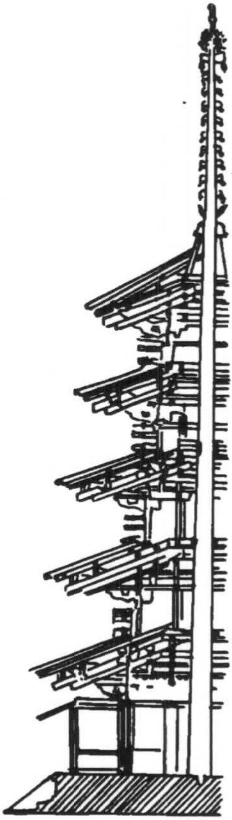


Fig. 108. The Japanese pagoda with flexible core

roof. The result was a kind of a multistorey structure, but only the first storey space was employed; the purpose of other storeys was to emphasize the significance of the pagoda as a whole. Storeys were made so that the perimeter poles supported a closed belt consisting of a few courses of logs laid horizontally like in the Russian izba. The belts formed the base for the poles of the next storey, and so on up to the top. The logs laid horizontally at the level of each storey are nothing more, from the modern viewpoint, than a seismic stability belt used to provide a horizontal bracing of the storey elements. From this point of view, the Russian izba is an entire antiearthquake belt.

Certainly, it is good that the pagoda diminishes in size with height, but it is bad that its structure is significantly complicated by the vertical posts broken at each storey. There is one more essential disadvantage in the pagoda structure, as far as the seismic stability is concerned. This is an excessive weight of the structure due to a heavy roof made of clay tiles. All these shortcomings are compensated for by the fact that the pagoda is a structural system consisting of two subsystems with different rigidity. The above-described structure from storeys with a heavy roof represents a flexible system. Its center is pierced by a still more flexible system in the form of a pole made up of a gigantic tree trunk or a few parts. This pole pierces all storeys of the pagoda and protrudes above the roof in the form of a spire mounted on which traditionally are nine bronze rings. The foot end of the pole rests on a stone base and is secured in it by a tenon, exactly like in the Central Asia columns. The outside skeleton and the internal flexible pole are connected to each other only at the level of two storeys. The whole of the pagoda is supported by a stone base. One of the secrets ensuring the exclusive seismic stability and the ability of these pagodas to stand to typhoons consists in that they comprise two subsystems of different rigidity. Earthquakes and typhoons that are dynamic in action, each having a prevailing period of oscillations, affect one of the subsystems, either the flexible or more rigid one, depending upon the period of oscillations. In this case, the other, as it were, the opposite subsystem will shake less and serve as the damper of oscillations suffered by the former subsystem. For the structure with this double rigidity system it is good practice to have the periods of natural oscillations suffered by the flexible and less flexible parts differ essentially. Maybe from this point of view, ancient builders were wise to make a heavy roof of the skeleton pagoda system, thus essentially increasing the period of its natural oscillations, and secure the central flexible pole at three points, thus decreasing the period of its natural oscillations. Therefore, they obtained a large difference between the periods of natural oscillations of the two subsystems comprising the pagoda. The result is known: the seismic stability of pagodas has been proved by their multicentury history, and I was wrong in saying that the heavy roof of pagodas contradicts the principles of earthquake-proof construction. I reasoned a standard way, while ancient builders approached the problem creatively. An example is a pagoda of the temple ensemble of Yakusidzi (Fig. 108) built in 680. The pagoda is a three-storey type, but looks like a six-storey one because of the balconies provided between the storeys. The central round pole is free to stand on a stone foundation and is 0.9 m in diameter. The height of the tower from the foot to the spire is 35 m.

The monastery architectural complexes also included temple edifices. Those buildings were also built of wood on a stone base. As a rule, these single- and two-storey temples were as complicated in structure as pagodas, less the central flexible poles, but with the same bracing in the form of horizontally laid logs at the storey levels. In the structure of these temples, we are interested in the timber beams that rest on columns with the aid of bolsters forming a spatial hinge. Generally, all joints of the horizontal, vertical, and inclined elements were hinged. The result was a very ductile system, a mechanism resting on a rectangular netting of the first storey columns. It would be good to check my guess. To my mind, this hinged joint skeleton system disturbed by an earthquake returns to the initial position by the gravity of its own weight, i.e. we deal herein with a unique system of earthquake protection.

An example of such a two-storey main temple, "kondo", is the monastery Khoryudzi in Nara whose construction was completed in 607. The elements of earthquake protection were, as before, represented by a rectangular netting of free-standing poles that raised the building itself above the ground in a manner indicated in Fig. 106. An example is the above-mentioned treasury Cesoin in Nara (Fig. 107). Like the Russian izba, it was built of horizontally laid logs, the entire structure being highly raised above the ground (the 8th century). At that time, an immense wooden building was constructed known as Daibutsuden, the hall of Great Buddha, related to the architectural monuments of the Nara period. Its dimensions (in plan) were 87 by 50 m and 49 m high; there were two pagodas, 97 m high. The hall of Great Buddha survived. Its two roofs were highly raised above the ground by a skeleton system, the lower part of which was formed by separate wooden columns performing the function of seismic insulators. A solid stone stage served as the base for the whole structure. The work of such stage under seismic conditions was discussed before.

What has been related about the monastery complexes of Japan refers to the monumental architecture, but I would like to give an example concerning the conventional residential construction. This simple example points to the well thought-out antiearthquake measures even in most usual cases.

In Japan, the following structure existed in the residential construction. Large stones were laid on a levelled course of gravel, which served as the base for slender wooden columns. Holes were drilled at the top of these stones to receive wooden posts, thus forming the base of the entire building. These posts supported a light roof with light wood-and-paper walls between them. Certainly, this was a highly earthquake-proof structure, each stone base moved in its own manner following the intricate ground motion during an earthquake, and, at the worst, only flexible ties between the posts could be broken. Moreover, the stones could slide over the gravel, reducing the motions conveyed from the ground to the structure.

Now we shall have a few stories dealing with the seismic stability of architectural monuments of China. With no risk to err from the truth, one may say that fully earthquake-resistant structures were created in China already during the Neolithic stage, i.e. at the turn of III and II millennia B.C. The walls of these buildings were made of poles driven into the ground and tied to one another with hemp ropes. All this was then smeared with clay mixed with straw. The light ceiling was made of wooden rods also rope-tied, clay smeared and covered with burnt tiles. In case of large spans, intermediate wooden columns were utilized.

The next period of history we are interested in is as follows. During the period of the Warring States (the 4th-2nd centuries B.C.) the temples, palaces and houses of nobility were erected on high earthen stages faced with bricks. One of such stages is known to be 18 m in height. You already know what an earthquake-proof measure is represented by a soft stage. There is evidence on multistorey wooden buildings and nine-storey towers related to that time. At the same time, they start building the monumental structures of stone: watch towers, fortress walls, and the like.

The burnt brick was also widely used in China. The high skill of brick structure builders is well demonstrated by many underground tombs of nobility. During the last centuries B.C. the tombs were laid of large hollow bricks. At the beginning of A.D. the use of smaller bricks commenced, and voussoir bricks appeared for laying vaults. Near the city of Baodin in the county of Vandu there is a large tomb completely built of bricks (the 2nd century). This tomb comprises several rooms ceiled by barrel or rectangular (in plan) vaults interconnected by narrow corridors. The bricks are laid on a lime mortar in compliance with rules with proper bonding and rounding the joints between the vaulted ceiling and the walls. In order to reduce the thrust, the vaults already have a raised profile. All entrance apertures are spanned, in addition to the major arches, by two more corbeled arches. The tomb is complicated in plan, but its individual halls are interconnected so that they can be displaced independently. Owing to all these measures and also due to the underground position, the tomb could stand for almost 2000 years.

Now let us drop in Korea in order to get acquainted with an ancient observatory. This tower of Stars—Chkhomsonde (647) was built in the south of the country (Fig. 109). This monumental tower is 9 m high. The tower is bottle-shaped, and its bottom diameter is 5 m and top diameter, 2.6 m. The tower is erected on a low stone base and laid of elongated cut stones of similar height forming 27 rings decreasing in diameter with height. An observation site is made on the tower top.

To discuss this tower from the earthquake resistance viewpoint, note first of all its unusual, very stable shape. In place of two cylinders placed on each other, which would be quite natural in this case, one cylinder gradually changes into another. The result was a tower of unique shape. Should the use be made of a structure comprising two cylinders, extra load-carrying structures for the top small cylinder ought to be provided inside the lower large cylinder. This would make the tower more complicated. The choice of the tower shape made this unnecessary. Besides, the shape chosen ensured no stress concentrations in the

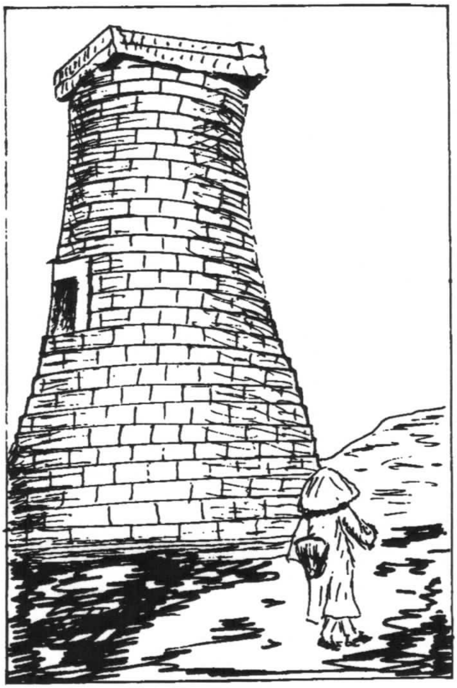


Fig. 109. Bottle-like geometrically stable form of the Star tower

tower. The tower design is ideally simple, to say nothing of its axial symmetry.

Now some words should be said about the uniform stone masonry of the tower. Needless to say, the elongated rectangular stones of equal height are laid with proper bonding. The thrust arising at the middle part of the tower is taken up by friction forces in the horizontal joints of the masonry. These friction forces are another go in the tower, the first being its shape. Recall the cyclopean masonry, say, that of Mycenae (Fig. 29). That masonry was made of stones differing in shape and size with no sliding planes. The resultant masonry was strong and rigid. In the tower of stars, however, the closed rings of masonry can slide relative to one another and deform in their plane, despite great thrust

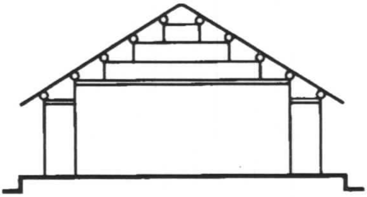


Fig. 110. Chinese thrustless gable roofs

overloads. The tower ductility develops because the masonry stones can slide with regard to each other along the horizontal joints. The result is that a rigid masonry tower features ductility. Looking at the figure (Fig. 109), you can see that the tower is deformed and shows deviations from the initial ideal shape. To my mind, these are the traces of earthquakes the tower stood to. These displacements and deformations have possibly saved the tower from collapse.

Let us now return to China and talk more about the wooden architecture. The structure of the buildings was based on a wooden framework employing the girder-pillar system. Even ridge roofs were made in accordance with this system (Fig. 110). Unlike the European roofs, where use was made of various struts causing thrust loads, no thrust took place here. Unusual were capitals with wooden columns (douguns) used in China. This is a self-balancing spatial system consisting of different-length brackets, which is a hinge through which no column motion is transmitted to the ceiling.

Talking about China, one cannot but speak of numerous and diverse pagodas of stone, brick, metal, and wood. As a rule, the pagodas have a good stone base and the above structure built in a most whimsical manner. There are pagodas with a heavy central trunk and a light structure attached to it. I want to draw your attention to an absolutely unique structure of wooden pagoda not yet encountered by us.

The only wooden pagoda that has survived till now is Sakya Muni of the Foguncy monastery built in 1056, the province of Shanxi (Fig. 111). The octahedral (in plan) pagoda is up to 66.6 m in height. DEVILISH SKILL, DIVINE ART is written on a plaque fastened

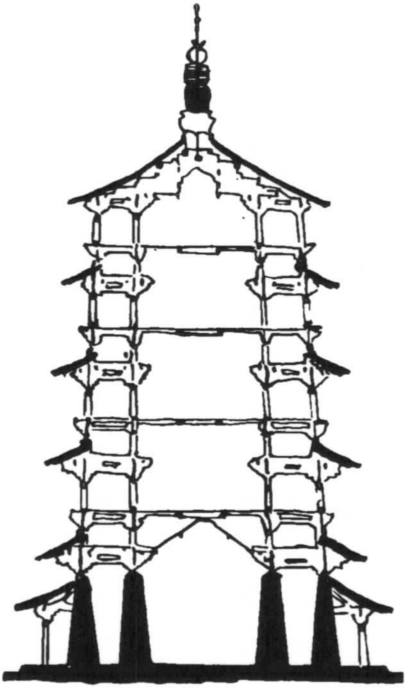


Fig. 111. Pagoda Sakya Muni—vibration damper

to the pagoda's base. We are concerned only with the skill and it remains to find out why it is devilish. Two octahedrons forming the walls of the inner rooms are laid of bricks for the entire height of the ground storey. The wooden structures of the upper pagoda storeys rest on these octahedrons. All the components of the pagoda skeleton are made ductile. In order to join the wooden poles and beams, which support the whole of the structure, use was made of more than 60 of dougun kinds—spatial hinges mentioned before. The resultant structure of the pagoda is, probably, more flexible than that of the Japanese pagoda with a wooden central pole. All the nine storeys are free to move with regard to one another in either direction.

The very essence is that there is a little brick platform on the top of the roof with moderately sized but sufficiently heavy metallic stupa. According to modern concepts, this is an actual oscillation damper. This additional weight increases the oscillation period of the whole structure, and during an earthquake it will behave as follows. Together with the ground will shake the stone platform of the base with rigid walls of the ground storey standing on it. Their amplitude will be the greatest, while the oscillations will diminish with height, from storey to storey, and the top mass due to its inertia will remain motionless. In some thousand years, we shall use similar dampers on TV towers. Certainly, only the devil could propose such an outstanding device to damp oscillations. Nobody else could hit upon this idea. It was simply illogical. To make the structure more reliable, it was necessary to carry a huge metallic billet and a heap of bricks to the height of 66 m, using the unstable wooden structures. This added to the weight of the entire structure contrary to the seismic stability principles with the resultant pagoda of improved resistance to earthquake that stood more than 900 years.

Of the diverse wonders of China, I should like to name the iron and bronze pagodas that were built in the country. Materials of which the structures are built are of utmost importance in providing the earthquake resistance of structures; this, I think, is clear. At that time bronze and iron were probably the best materials from the standpoint of earthquake resistance. An example is an iron 13-storey pagoda, 21 m high, laid of cast-iron plates and erected in 1061, the province of Hubei. This pagoda draws our attention by its extreme slenderness. Its height-to-base diameter ratio is equal to 10. However, the pagoda still survives and stands well to winds and earthquakes. This points to good ties between the cast-iron plates. How are these ties made? I should like to know it myself.

There is no escape from mentioning the temple of Heaven of outstanding architecture, which was built in Peking at the beginning of the 15th century (Fig. 112). This wooden temple features the ideal axial symmetry. Even the high and wide stage on which this round temple is erected is shaped like a truncated cone. As to its design, the temple of Heaven represents a conventional skeleton system whose basis is formed by two rows of columns secured in the base stage. These columns situated in a circular manner are reinforced by four still thicker internal poles

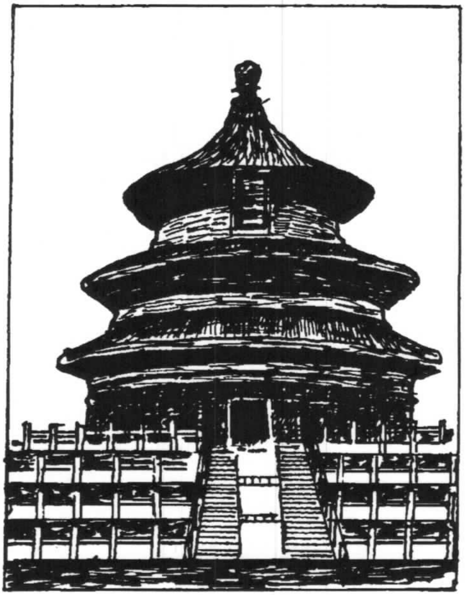


Fig. 112. Centric wooden edifice of the temple of Heaven

supporting the upper of the three storeys. All these columns of different height are jointed by a system of horizontal ties into a single spatial skeleton. It's a pity that I can find no disadvantage in this structure, from the standpoint of earthquake resistance, to demonstrate my erudition. In a literal sense, all principles of earthquake-resistant construction are implemented in this temple that stands on a stage partially reflecting the earthquake waves. The flexible wooden columns supporting the temple roof storeys perform the function of seismic insulators. The whole of the structure has an ideal axially symmetric pyramidal shape. The material of the structure is wood. In addition, the central and peripheral parts of the temple differ in rigidity. Both parts act as oscillation dampers with regard to each other.

Much can be said about Chinese pagodas, towers and temples. There is something to each of them, but this discussion is beyond our task. A separate book should be written to deal with it. Our task is to dig up structures we are interested in from the history, try to understand their gist from the viewpoint of seismic stability, and to move further with a view to better satisfying our curiosity.

Here is one more small essay related to two types of Chinese bridges.

Very popular in the mountainous regions were rope suspension bridges. The major components of these bridges were, naturally, the suspension ropes. Bars horizontally laid on the lower ropes formed the board decking for the traffic. The side ropes and vertical posts formed the handrails. Powerful stone supports to which the suspension ropes were attached were made on both banks. Frequently, these supports had special devices to control the tension of the ropes. The suspension bridges were up to 150 m long and 2.5 m wide. The suspension bridges employed not only ropes, but also iron chains; the latter bridges were more durable. In 1701, in the province of Sychuan, the bridge of Ludintesotsyao, 100 m long and 3.0 m wide, was built across the river of Dadukhe. Its wooden decking was laid on nine chains about 9 cm in diameter each. The bridge was additionally suspended from two ropes above. The handrails were also made of iron chains. The structure of the suspension bridge is ideally flexible and whatever asynchronous motions of the bank supports cannot ruin it.

The other type of bridges, arch multiple-span bridges, found its application in the plain area of China. The arches of diverse shapes, from semicircular to elliptical and lancet-like, were popular. Special emphasis was put on the strength of the bridge. To provide good bonding between the stone blocks, they were laid on a lime mortar to which bull's blood and sticky rice were added to improve adhesion. Frequently, these bridges were built on low-lying lands, hence, on bad grounds, plus the probable danger of earthquake. All this was well understood by ancient architects who did their best to preserve the structures they erected. In this case, in addition to the masonry strength, use was made of a pile base. Besides, in order to improve the reliability of the bridge structure, the spans of bridges comprised, as it were, a set of arches each of which could work independently, and if some arches failed, the remaining ones could carry the bridge load. The eleven-span bridge of Lugoutsyao, across the river of Yundinkhe, was built 15 km

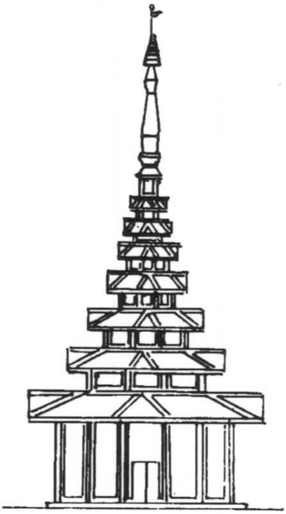


Fig. 113. Pagoda—a flexible wooden structure

from Peking. It was 235 m long, 8 m wide, and had 437 decorative sculptures. The bridge was built of lime plates and already existed in the 6th-7th centuries; in the 13th century Marco Polo rode over this bridge. This is one of the most famous and durable bridges of China.

Searching for structural designs that are interesting for us, let us go to Burma. Without going into the involved history of that country, we shall proceed to considering its actual architectural monuments.

First of all we shall get acquainted with the Burmese traditional pagoda. This is a wooden tower-like edifice that looks like Japanese and Chinese pagodas. However, the Burmese pagoda was used more universally. It was used as the decoration of monasteries, throne-rooms of palaces, and fortress towers. The large Burmese pagoda of the palace in Mandalae without decoration is shown in Fig. 113. In spite of apparent complexity, the Burmese pagoda is noted for structural logic and simplicity. It is always square in plan and has a fine-pointed pyramidal outline. The load-carrying structural components of the high ground storey are log poles. The tops of these poles are tied by a rigid framework. Placed on this framework is a heavy cross piece supporting the log that threads the upper part of the pagoda. There is a separate framework made of wooden bars at each storey level of the pagoda. All the frameworks of storeys and the vertical pole are interconnected by a system of struts to form a single, strong, geometrically stable and light, spatial structure. Herein we again deal with a well designed, seismically stable, wooden structure that was improved for ages. The light pyramidal body of the pagoda is raised by strong, flexible, wooden columns above the ground. These columns serve as seismic insulators for the upper part and provide the seismic insulation of structure from earthquake waves approaching the pagoda from any direction. Not an unimportant role plays here the thick wooden pole clamped by the structure and highly protruding above it. This is a sheer damper. The natural oscillation periods of this pole and the pagoda structure itself most likely do not coincide. This restricts the structure's swinging due to both earthquakes and gusts. To this I will add that this pagoda is based on a low brick stage.

In the highly developed (for its time) construction technology of Burma, burnt brick of large size (38 by 18 by 6 cm) was utilized more often than wood. Clay or lime mortar was employed for brick masonry. Like in Central Asia, use was made of various mortar additives, such as sap of lacquer tree, powder of dried and stamped hide of buffalo, and something else. The purpose of these additives is unknown, maybe to impart ductility and better bonding properties to the mortar. They knew how to erect 8-9 m span vaults. Duplication- and corbeled-arch systems were popular. Wood was used to reinforce the masonry. The temples erected by this technique of brick masonry well stood to a severe earthquake in 1975. Here we have two examples of edifices built of bricks.

Of the worship edifices of Burma stupas come to the forefront. There is even a saying that at least one stupa can be seen from any point of the country. Probably, the stupa originates from a burial mound for which reason this centric structure has no internal room and serves as a container of a sacred relic. There is a variety of stupa forms, though all these forms have three inevitable elements that include a base stage, a bell-like body of the stupa, and a

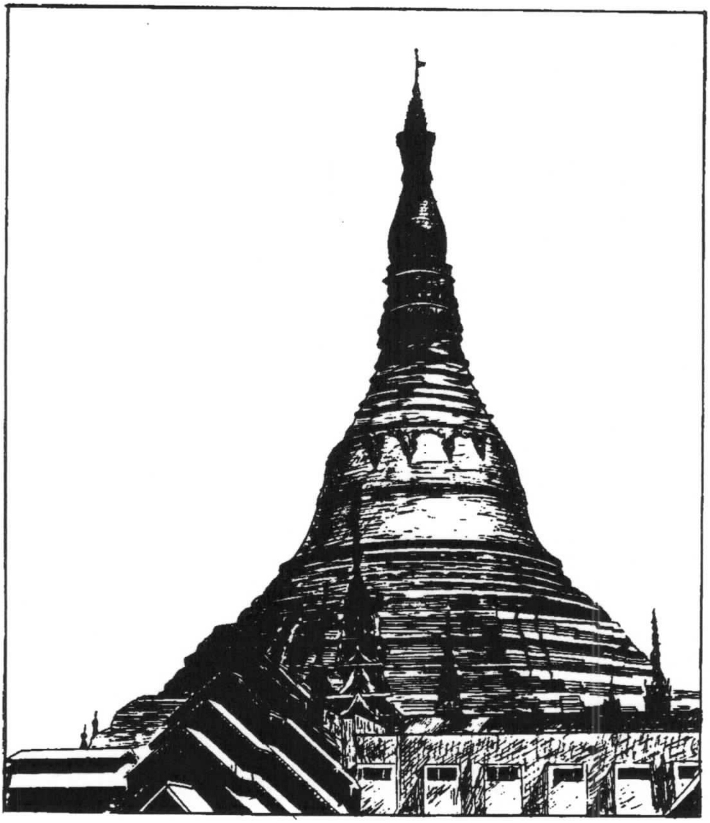


Fig. 114. Shwe Dagon stupa—one more stable geometric form

crowning spire. Located near Rangoon is the temple complex of Shwe Dagon known not only in Burma, but in all South-East Asia. By tradition, it was founded 2500 years ago. The 20-m high gold stupa then built is believed to contain eight of Buddha's hairs. The trustworthy information about this stupa refers to the 14th century. In any case, after many added on construction improvements, by 1774 the Shwe Dagon stupa looked like today and was 99.5 m high above the stage (Fig. 114). The rectangular stage of Shwe Dagon is 214 by 275 m in size and 20 m high. The stupa is somewhat shifted to one of the stage edges, rather than placed centrally on the stage. From the standpoint of earthquake-proof construction, the Shwe Dagon stupa is O.K. in all respects. The axially symmetric, stable, cone-like body is placed on a bulky, large-size, rigid stage (platform). It can not be said, however, that the stage and the bell-like part of the stupa are monolithic and homogeneous. All these elements have gained their modern dimensions as a result of many construction improvements. As a rule, in such cases a new stupa, larger in size but exactly of the same form, was built around the existing one. The result was an axially symmetric layered structure.

A stupa on a stage may be fancied as a large ship in a turbulent sea of earthquake waves. This ship slowly swings on small waves chaotically attacking it. In principle, a person standing on the balcony around the stupa should feel no earthquake shocks. However, mentions were made that this stupa was troubled many times by earthquakes. What is the matter? Maybe it is accounted for by the heterogeneity of the stupa structure, or maybe the earthquake waves in this area are of the same length as that of the stupa.

Many brick temples survived in Burma. The major disadvantage of these temples is a high bulky ceiling. However, this disadvantage is compensated for by the pyramidal form of the temple and its wide base. Till the 12th century all temples were practically centric. Later more pretentious and intricate temples were constructed that lost their centricity. Of all numerous structures of Pagan my attention was drawn to the unique structure called Pitacatay (a repository for holy Buddhist texts), the plan and cross section of which are shown in Fig. 115. This structure strikes by pure design and the absence of unnecessary elements. To my mind, from the viewpoint of seismic stability, the best found in the temples of Pagan was implemented herein. This edifice was erected in 1058 and overhauled in 1788. The book depository is situated at the centre with a passage corridor around it. The result is that the edifice square in plan has two planes of symmetry; it stands on a small stage. Generally, the entire edifice looks like a pagoda built of bricks rather than wood.

In Vietnam I want to invite your attention to a single structure, i.e. to a small temple built of wood and stone, called Mot Kot, and

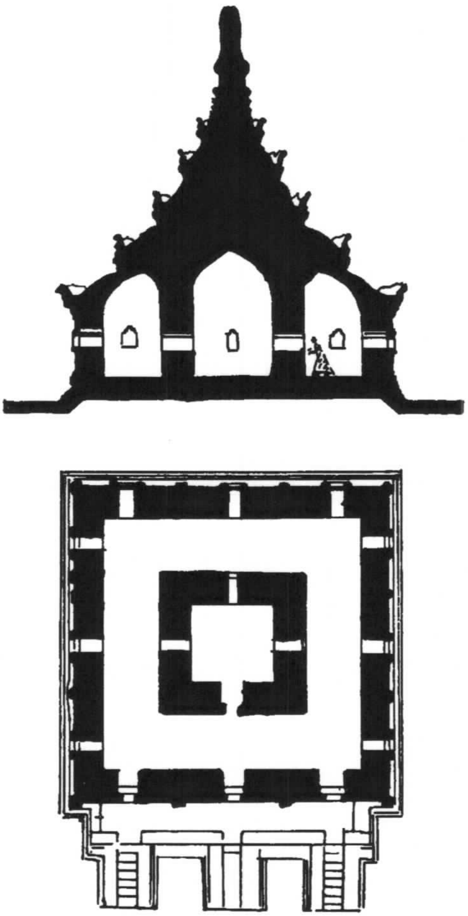


Fig. 115. One more example of symmetric temple with perfect geometrical proportions

erected in 1049 (Fig. 116). This temple is built so that its base is a large, round stone column. Eight inclined wooden beams corbel out of the stone column to bear the timber columns, members of the structure skeleton that support the temple. From the builder's viewpoint, the result was a point-supported building, the idea of

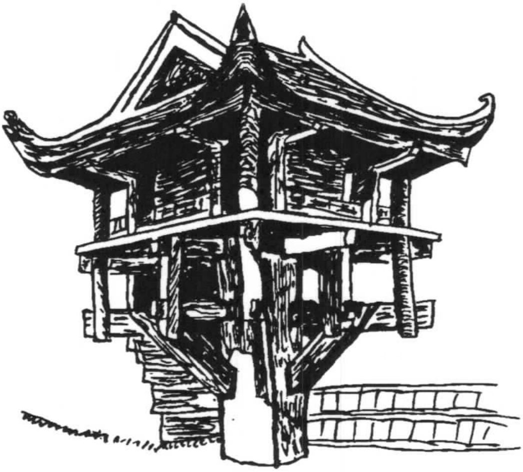


Fig. 116. Mot Kot temple supported by the only column-foundation

point support being carried to its ideal or absurdity, as you like. Let us analyse what can be yielded, from the standpoint of seismic stability, when a building rests on one column deeply dug in the ground. First, the surface earthquake waves do not menace this building with damage, since its support is located at such deep levels where there are no surface waves at all. Therefore, the problem of allowing for the unequal motion of a seismic field under the structure does not exist in this event, like in the case with a long building. Second, due to the point support, no twisting caused by the nonuniformity of the seismic field will be transmitted to this building. Third, the ground base seismic waves will be averaged along the height of the foundation-column, rapidly diminishing with depth and the vertical oscillations of this column will be minute. In short, a building foundation made in the form of a column dug to a depth of 30-40 m is an effective antiearthquake measure. However, it is not easy to erect, say, a 16-storey tower-type building on such a foundation-column. The present-day pile foundations feature certain advantages of the foundation-column.

Now let us set off for India which we disregarded for the present, though there is much to see. No less wonders exist in India than in China: temples with flat and highly raised corbeled domes, underground temples, Taj Mahal mausoleum, domed mosques—all these are situated in highly seismic regions. I want to utilize this variety in order to draw your attention only to two features that are interesting from the standpoint of seismic stability.

You know well that the homogeneity and solidity of the material are important requirements imposed on earthquake-proof structures. This particularly applies to brick and stone structures. Indian architects were also concerned with the solution of this problem and tackled it in a very unique way. They set about and cut the temple of Kilasa in Ellora completely of rock. Its dimensions are 50 by 33.2 by 32.61 m. No other architectural monument, so vast and completely chiselled of rock like a statue, exists in the world. There is no need to discuss such important properties of earthquake-resistant structures as the uniformity of masonry, good bonding, and mortar adhesion in this edifice, since it goes without saying. There were also other edifices chiselled completely of a solid rock, though not so huge, but also well proportioned.

Now the other fact we are interested in. These are underground structures cut directly in a mountain mass. We did not yet discuss such structures, though they are encountered everywhere. Characteristic of Egypt at the time of the Middle Kingdom is the type of the rock-hewn tombs. It is known that Petra—the capital of Nabataea, the ancient Arab kingdom, existed already in the 4th century B.C. and was a city almost completely rock-hewn in red sandstone rocks. However, rock-hewn structures were particularly popular in India. As early as the 2nd century B.C. a whole complex of rock-hewn Buddhist monasteries existed in Ajanta. The rock-hewn construction of Buddhist edifices in Ellora, which was more perfect from the architectural viewpoint, was started in the 6th century and completed in the 10th century. Two- and three-storey edifices were hewn in rocks. The three-storey Buddhist temple Tin-Tkhal is the largest and most interesting. The ground storey is a multicolumn hall—the main shrine. The next storey also houses a multicolumn hall and also side galleries on whose walls the scenes of Buddha's life are cut. The hall of the top storey is cross-shaped and is surrounded by monks' cells. The support poles were hewn solid with formed bases and capitals. Naturally, in these rock-hewn edifices the principles of earthquake-proof construction, such as the monolithic and homogeneous material of the structure, deeply laid foundations, closed contours of load-carrying structures, were fulfilled automatically. Moreover, as was said above, the underground layout reduces the very effect of earthquake shocks and shaking. In short, these rock-hewn edifices stand well to earthquake effects. I know only two cases of calamities that happened to such underground edifices during earthquakes. This was not without reasons that are as follows.

A catastrophe the consequences of which may be compared to the disaster of Atlantis occurred in China, the province of Shanxi, in 1556. Then 830 000 people were killed. Traditionally, the majority of population lived not in houses, but in multistorey caves that were dug in dense, but ductile thickness of low-strength loess. The property of this loess in the dry state consists in that at shocks and vibration it disintegrates into fine dust flowing almost like liquid. This property of the loess played the fatal role. During an earthquake that took place, the tremendous shocks and vibration disintegrated the enormous bulks of loess on the mountain slopes bored by human dwellings into dust which buried about a million of human beings.

A similar event took place on the territory of this country two centuries earlier than in China. Some years ago in Georgia people celebrated the 800-year anniversary of the cave monastery named Vardziya built as a defence complex at the time of tsaritsa Tamara. The monastery was arranged within a mountain slope and had no less than seven storeys of dwelling cells spacious enough to hide the local inhabitants in case of danger. Besides, there were a temple with frescos, water-supply system, sewage system, several internal ways down—all this badly affected the mountain slope. When an earthquake occurred, the not strong rock, like shell rock which is readily cut by a conventional metal chisel, failed being weakened by the system of bores. A shear occurred along the slope, and the resultant landslide revealed the internal architectural system of the ancient monastery. The whole of this multistorey system of caves can be seen today [7, 48].

After the brief acquaintance with a huge geographical region, including many centers of ancient civilizations, and considering only what has attracted our attention, we shall set off for the pre-Columbian America.

Seismic Stability Of Structures In Pre-Columbian America

Now we are in America. Here, as usually, we shall briefly familiarize ourselves with the construction techniques of ancient peoples living in America before it was conquered by Spaniards in 1519. It would be worthy of saying that, on the one hand, in the New World we shall encounter other unique structures, absolutely unlike those we have seen in the Old World. The oceans separating the two worlds have played their role. On the other hand, there is much in common in the human logic. Besides, some relationship, probably, existed between these two worlds in past times, for which reason construction techniques are encountered very much like those we considered before. So, go ahead.

By the time the Spaniards arrived at America, there existed many slave-owning city-states. The Toltec culture spread in Central America, the Inca culture—in the Andes. It is curious from the builder's viewpoint that no metal was used even in the most grandiose structures of the ancient American Indians, except maybe the mountain regions of the Andes. The stone trimming was made by stone tools. The lime mortar and burnt brick were known. The voussoir arch was not devised, and corbelled vaults were employed.

Not far from the modern city of Mexico in a valley frequently shaken by vigorous earthquake shocks, Kuikuil'ko, one of the most ancient pyramids, is located. It was erected before 500 B.C. This is a round, four-step, rather flattened structure with the base diameter of 135 m and a height of about 20 m. The pyramid is laid of large boulders immersed in clay. This is another example of a structure resistant to earthquakes. The fairly flat loose bulk of the pyramid body will breathe together with the ground surface during an earthquake without being destroyed. Probably, this multistep, round pyramid of stone and clay possesses the same resistance to earthquake effects as the rectangular stepped ziggurats of Babylon built of unburnt bricks. To the point, they are related to the same time. Like in Babylon, where the ziggurats served as a stage-base for temples, the altar in Kuikuil'ko was placed on the pyramid protecting it against floods and other natural calamities. To the point, Kuikuil'ko was left by the inhabitants because of an outbreak of a volcano, so that the lava covered the city and the foot of the pyramid. The lava did not reach the altar.

In the high-mountain valley of Mexico, Teotihuacan was the largest city of pre-Columban America, the 1st millennium A.D. This city had the worship center, including the pyramid of the Sun as the most important structure. This was a rectangular four-step pyramid (the 1st century A.D.), 210 by 200 m in size (in plan), 65 m high. The design of this colossal structure was as simple as that of the above-mentioned pyramid in Kuikuil'ko. It was built of boulders immersed in clay mortar. From the standpoint of seismic stability we are more interested in the pyramid of the Moon (the 3rd century A.D.), which was included in the same worship complex known as Teotihuacan. The construction of this pyramid was more perfect. The design of the pyramid was based on the principle of constructing the earthquake-proof three-layer walls consisting of two intertied stone facing courses and a softer core which we discussed. Besides, there were the pyramidal stable form and symmetric spatial system of stone walls forming closed contours. The design of the pyramid of the Moon is shown in Fig. 117. Its skeleton consisted of a tuff masonry rectangular grid whose voids were filled with rubble on a clay mortar. We did not yet encounter this design of pyramids. Perhaps, in Babylon, some important structures of the Hanging Gardens type were built of air-dried bricks and reinforced with stone poles. Here the design was more perfect. Note that the pyramid of the Moon was 120 by 150 m in the base size and 42 m high.

This was a "classical period". In the next period of development (the 10th-13th centuries), the leading position was taken by

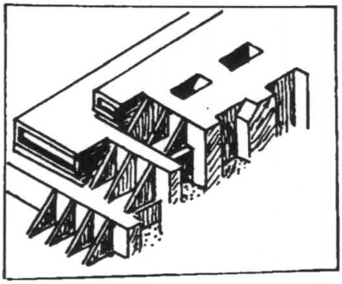


Fig. 117. Stone skeleton of the pyramid of the Moon

Tollan, the capital of the Toltecs. Here the worship center was laid out on a natural platform (stage) prepared for the purpose. The hill top was levelled, while the hill slopes were reinforced by support walls. We may say that this was a general seismic stability measure. However, there is no progress in the pyramid construction techniques in this case, most likely, the other way round. The stone grid skeleton was no longer used in pyramids. A large pyramid in Tollan, 65 m in the base side, was made of stone and earth. The pyramid facing were thin carved plates secured by special protrusions from the pyramid body. But it is a shrine built at the top of the pyramid that we are most interested in. The flat ceiling of the shrine was supported by two rows of stone supports, 4.6 m high. The first row comprised atlantes (Fig. 118)—powerful figures of warriors. The other row included simple squared columns consisting of rectangular stone blocks. The warriors were also built of separate blocks. All these blocks were interconnected by wooden tenons. Exactly as in ancient Greece with the same effects. The rigid walls of the shrine failed, while the ductile columns-warriors survived.

The Maya peoples lived on the peninsula of Yucatan. Like the case was with the Mexican plateau, the Mayan cities included monumentally built religious administrative centers surrounded by huts of crop-growers. Here use was made of lime mortar, for which reason the cores of walls, pyramids and stages were built of rubble and earth poured over with a lime mortar. This allowed construction of higher pyramids which looked more like towers.

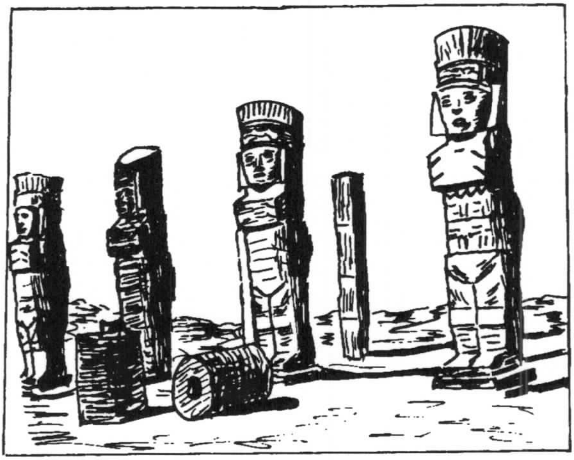


Fig. 118. Columns-warriors comprising separate blocks

One of the pyramidal temples in Tikal, the main city of the Mayas, was 70 m high, its base being 58 by 53 m.

From the standpoint of seismic stability, in the Mayan structures our attention should be drawn to the following. All monumental structures were erected on man-made or natural stages. The whole of the palace group of structures in Palenque was built on a stage, 10 m high, which in addition was surrounded by a wall. Because of the lime mortar the pyramid and stage structures were rigid. The very form of pyramids was stable with a low center of gravity. An example is the main pyramid in Etsna, the 12th-13th centuries, shown in Fig. 119. It looks very much like a multistorey building. Almost all pyramids were topped with seemingly disproportionate high ridges, but obviously measures were taken to reduce their weight.

Now a few words should be said about a more advanced civilization that arose in the Andes, South America. Consider a few examples typical for architecture of the Incas.

In the 3rd century the city of Tiahuanaco was founded on the banks of the Titacaca Lake, at an altitude of 3825 m above sea level. The city consisted of three groups of buildings, each being

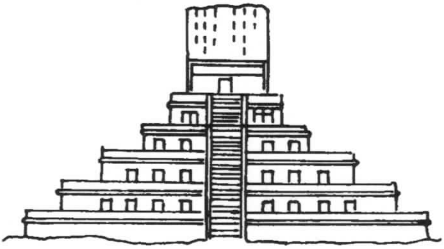


Fig. 119. Temple pyramid in Etsna, the 7th-8th centuries

erected on a gigantic ground stage faced with well surfaced stones. One of these stages was 210 by 210 by 15 m in size. Gigantic blocks of some structures (Fig. 120) were found among the ruins of the third group of buildings named Puma-Punku—a double pyramid. The weight of these blocks reached 200 tons. It is surprising that the blocks dressed with the aid of bronze tools only featured shaped configuration and accurate geometry. In assembly the blocks accurately fit each other and had the appropriate recesses that allowed them to be connected to each other by stone tenons and T-like bronze cramps. True, all these ties were not lead sealed, as the Greeks did, but the blocks were far larger, fit and engaged each other. The huge weight of these blocks resembles huge weights of Egyptian structures.

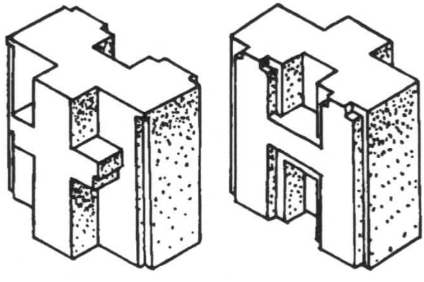


Fig. 120. Gigantic-shaped construction blocks of the Incas

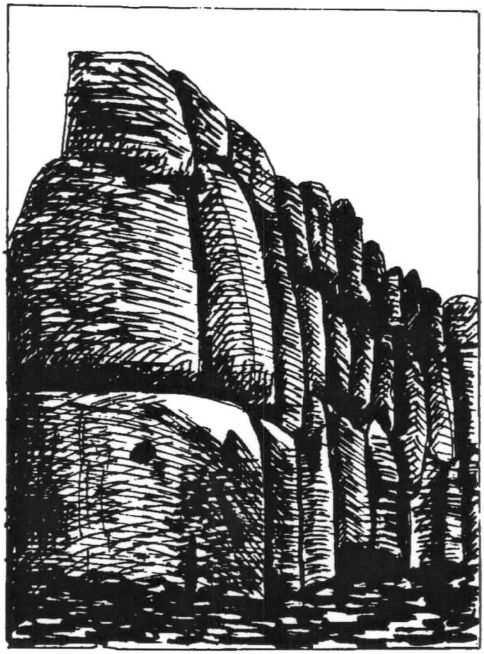


Fig. 121. Cyclopean masonry of the Incas fortress wall

The 12th century in South America saw the formation of the Incas state whose architecture merits special attention. They were skilled engineers and built palaces, temples and storehouses in Cuzco as their capital city. The walls of those structures survived. A fragment of a fortress wall built in the middle of the 15th century, north-west of Cuzco, is shown in Fig. 121. This fragment is part of the defence walls of the fortress named Sacsahuaman (Falcon's nest). The defence system of this fortress resembles very much the Greek Mycenae. The fortress was built on a mountain with steep slopes. On two sides it was protected by deep hollows. Three walls were erected on the third side where a passable saddle existed. The above figure shows that like in the case with Mycenae, the walls were dry-laid of huge grey-granite blocks fitted to one another so accurately that, according to some scientist, "even a hair could not be inserted between them". The walls were

Fig. 122. Polygonal masonry of walls in Machu Picchu

about 3 m thick and up to 6.5 m high. Separate blocks were 3 m wide and 6 m long. It was already discussed how the wall worked during an earthquake, which was built of cyclopean dry-laid stone blocks thoroughly fitted to one another. Note that in this case the Incas built their walls on mountain slopes, and to ensure general stability, the walls (in plan) were sharply zigzagged. Besides, 3 km of the walls had 40 counterforts also to support them.

Your attention should also be drawn to Machu Picchu, a fortified Inca town in Peru (the 13th century) in the construction of which cyclopean masonry was also employed. Many such fortresses were constructed in the empire of the Incas, and their magnificence and thought-out strategic position strike us up till now. The walls of temples, palaces and fortresses in Machu Picchu that were made of polygonal stones thoroughly fitted to one another and dry-laid stood well to the effects of time and elements. A man, however, has got to them to actively ruin. This wall is shown in Fig. 122. You see how perfectly and smartly the stones are fitted to one another so that there are no slide surfaces and none of the stones can be removed from the wall body. Moreover, I have information available from some sources that separate wall stones contact each other with the aid of semispherical keys to provide ductility (Fig. 123). I do not yet know whether there is deep sense in it, except for better adhesion between blocks.

There exists a legend in South America that fortresses of the Incas were built by gigants who lived there until a contemporary

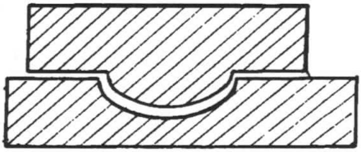


Fig. 123. Semispherical key joint of stones

man arrived. If you remember, there is a similar legend in Greece. Actually, it is as difficult to grasp how the Incas managed to move huge stone blocks from the quarries to the construction sites without using wheeled transportation means, how these blocks of enormous weight were chiseled, lifted and fitted to one another as to fancy infinity. So, whether you like it or not, you will believe any legend, any hypothesis dealing with strangers from space.

The last curious fact from the history of the Incas architecture and generally the history of earthquake-resistant construction that I attempted to write is mentioning the famous suspension bridges over deep hollows built by the Incas. The bridges were used by the local inhabitants as far back as the past century. A cable thicker than a human body was plaited from three very thick ropes. These cables were then carried over the abyss and permanently secured in the stone supports chiseled in rocks. The bridge decking and all other parts of the bridge were secured to these strong cables. To my mind, there is no need to explain that the flexible, light, though long, structure of a suspension bridge can, in principle, withstand the earthquake effects [7, 49].

To complete this work, we have to consider a few facts concerning the earthquake-proof construction today.

A Few Words On The Modern Earthquake-Proof Construction

My story of contemporary earthquake-resistant construction will be as concise as possible. There is no point in presenting it in detail. I acquainted you with the principles of earthquake-resistant construction, using the examples of ancient structures. The information about today's structures is so vast that a separate book should be written about this, rather than one chapter. There are no popular books on the modern earthquake-proof construction, while there are plenty of special engineering books on the subject.

From the modern viewpoint, there are two methods of erecting the earthquake-proof structures. The first consists in erecting a structure of increased strength so that it cannot be destroyed by an earthquake predicted in a given locality. The other, specific measures that are taken in order to reduce the probable earthquake loads in the structure caused by motions transmitted to it from the ground. These measures are as follows. First, seismic insulation is provided between the foundation and the building structure above the foundation whose purpose is to reduce the connection between the ground and the structure. Suitable are rubber-metallic spacers, various sliding strips, balls, various bodies of revolution, suspended structures. Second, use is made of engaged and disengaged ties that protect buildings against probable resonance phenomena. The purpose of these ties is to control the rigidity properties of the structure. Third, the damping ability of the structure is increased in order to improve its oscillation energy dissipation during an earthquake. Finally, fourth, dynamic dampers of oscillations that are utilized in order to convey some part of the energy produced by seismic oscillations of the structure to the damper.

I will give some examples of structural techniques in compliance with the second method as most interesting in constructing the earthquake-proof buildings. Remember that there exist structures which in principle are earthquake-resistant and need no specific aseismic measures. In past times, for example, these were represented by rope- and chain-suspension bridges. Today, examples are various air structures made of soft, light, air-inflated shells.

Figure 124 shows a system of building seismic insulation where rocking supports placed between the foundation and the building are utilized. The ends of the supports are rounded in order to make the building return to the initial balance position owing to its weight, if the balance position is disturbed during an earthquake. These rocking supports essentially reduce the level of shaking transmitted to the building from the foundation in an earthquake. Allowing for the high ductility of the seismic protection employing rocking supports, an additional system is designed to increase the damping of the whole structure aided by a cantilever and loads sliding over each other. In exactly the same manner, any of the above elements of antiearthquake protection can be arranged between the foundation and the building part above the foundation.

An earthquake-insulated system of the pendulum type in which the building is suspended by means of special studs is presented in Fig. 125.

Figure 126 shows the design of a support that has a tough lock ring between the upper and lower cases of the rubber-metallic cylinder. This lock ring is selected so that at a certain seismic load the ring fails and the rigid tie becomes disengaged. Accordingly, the building settles down on the rubber-metallic supports which become engaged. In this event, if the building has got in resonance, it leaves this state with modified rigidity.

An example of the design of mechanisms that increase damping of the building is as follows. The first storey fragment of a skeleton building is shown in Fig. 127. This type of building features decreased damping. To increase the damping, a steel cable

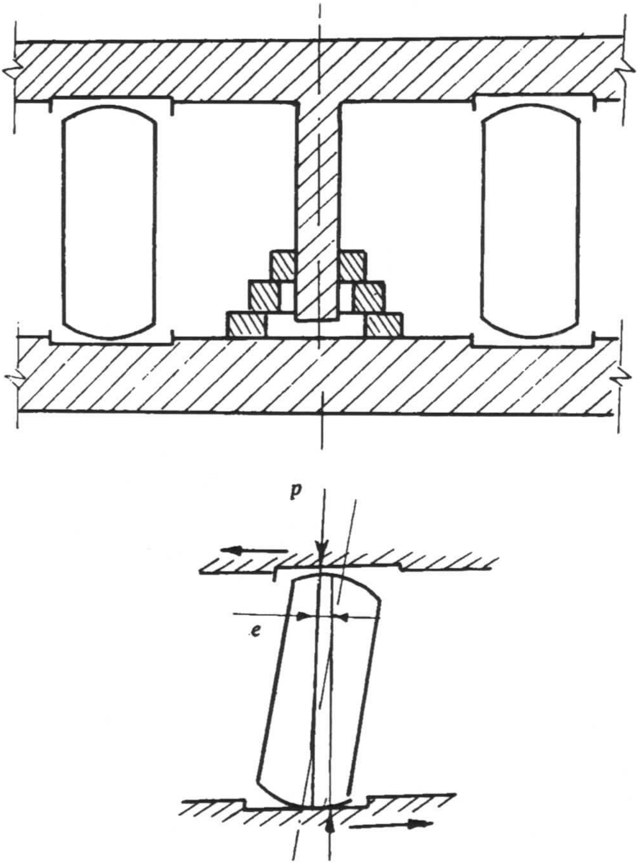


Fig. 124. Seismic insulation using rocking supports

is tensioned in accordance with the diagram shown in the figure. A clamping device is also used, which controls the cable motion by facilitating or impeding it. As a matter of fact, this clamping device may be employed to adjust the building to a certain required frequency of oscillation. Besides, the same scheme can be used for automatic adjustment of the building to the required regime. To this end, a geophone is required to record the earthquake taking place and to transmit it to an analyser which at once decides

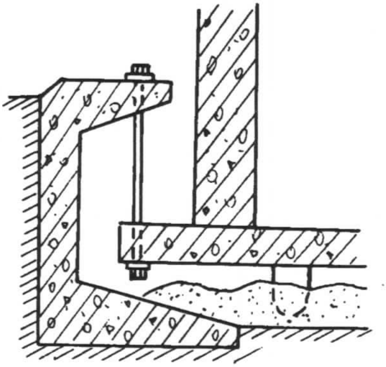


Fig. 125. Earthquake-insulated suspension system

whether a given earthquake is dangerous for the given structure. If the earthquake is dangerous, the analyser sends a command to the cable clamping device to change the rigidity parameters of the building as required. These systems of automatic control of the building parameters have found application in Japan. The system can even use the satellite-assisted communication.

An example of using the dynamic dampers of oscillations in the earthquake-proof construction can be represented by the television tower in the city of Alma-Ata. It is 372 m high, 18.5 m in the base diameter, and 4760 tons in weight. For the first time such a tower is built in a highly seismic mountain region. At an altitude of 248 m four pendulum-type oscillation dampers with a total weight of 40 tons are suspended in the tower. Their purpose is to dampen tower oscillations caused by gusts and earthquake effects. The operation of these dampers is based on the fact that their natural period of oscillations differs greatly from the natural period of tower oscillations. The tower oscillations caused by wind gusts are reduced to about 1/4 of their amplitude by these dampers. It only remains to see what will happen in severe earthquake.

Sometimes, the above-mentioned methods of protection against the earthquake effects are for some reason called nontraditional, implying, perhaps, that they had not been used before. The reader who has read this book to this page can be convinced of the opposite.

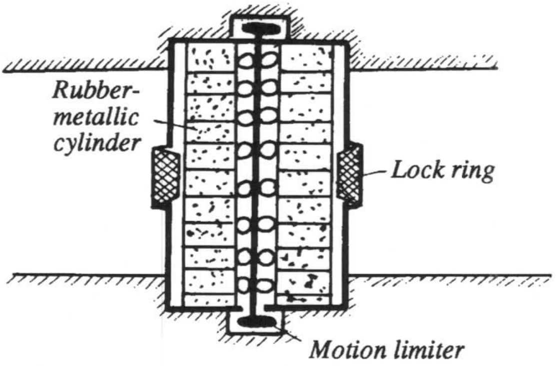


Fig. 126. Rubber-metallic earthquake insulator with disengagible tie

In extreme antiquity there existed various systems of seismic insulation and even of vibration damping. Lots of seismic insulation systems are designed in our time, which reminds me somehow the situation with designing perpetual motion: there were many designs, and each author believed only his project to be correct. Reaching a deadlock, this feverish excitement still played a positive role in the evolution of the theory of mechanisms. The same happens to the systems of seismic insulation. After each severe earthquake the research and design institutes are flooded with proposals for protecting buildings against earthquakes. In addition, the research workers and designers of these institutes have also much to do. Some of the resultant inventions may be published in comic magazines, some have theoretical, cognitive sense as they show the human aptitude for fantasies, but something can really be used in the practice of earthquake-resistant construction. I do not want to be an exception and shall make a proposal not yet made by anybody, a proposal that combines all four methods of antiearthquake protection. Please, turn it over in your mind and estimate. To the point, in practice a seismic protection method is never used solo. As a rule, it is combined with other methods. For example, balls used together with springs returning the building to its initial position are supplemented by a damping system, or sliding strips are used together with soft limiters of motion.

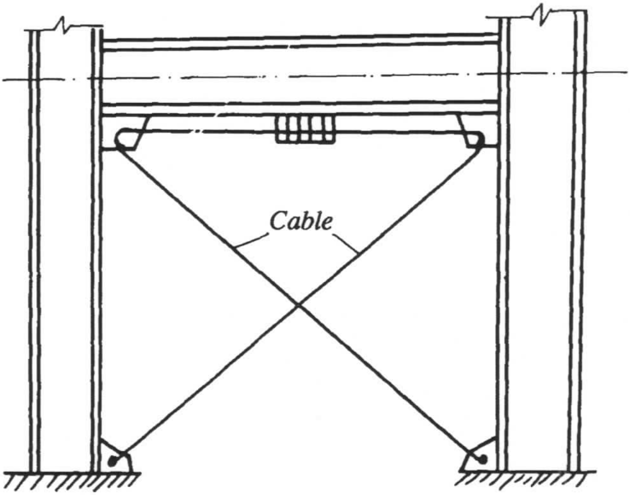


Fig. 127. Fragment of building with controlled rigidity

What I propose as an exercise to the material covered is shown in Fig. 128. In this event, as you see, the building stands on balls and is free to roll in any direction, depending upon the direction of the earthquake shock. The building cannot roll too far at once, inasmuch as it is anchored to the weights lying on the bottoms of pits. Naturally, the steel cables connecting the building to the weights are somewhat preloaded (pretensioned). In this case, the starting motion of the building will make the weights start their work. It only remains to discuss the operation principles of the proposed system of earthquake protection.

During an earthquake the building will tend to move some distance and turn. The turn will be associated with different kinds of asymmetry, such as fields of earthquake effects, position of the building center of gravity, nonuniform work of the support balls. A great advantage of the system proposed lies in that whatever complicated motion may be started by the building, the weights begin working to uniformly counteract this motion and, due to their gravity, return the building to the initial position. In short, the system proposed combines all types of special antiearthquake

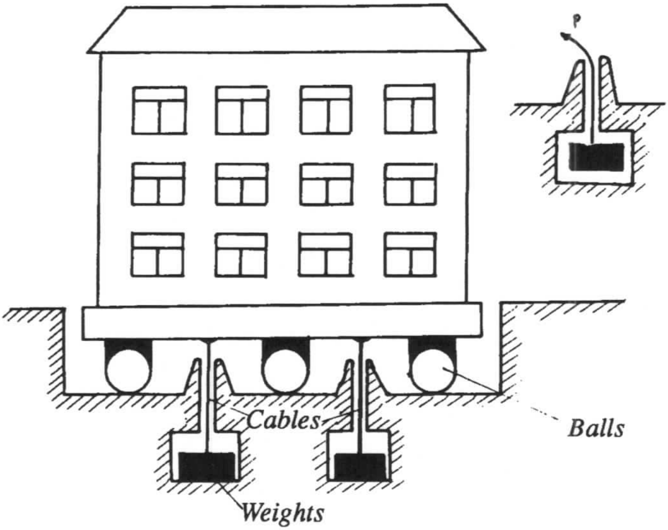


Fig. 128. Building with gravitation system of seismic protection using ball supports

measures: seismic insulation by balls, engaged/disengaged ties in the form of weights lying on the bottom of the weight pits, and increased damping because of cable friction against the walls of holes through which the cables are threaded. Finally, the weights unstuck from the pit bottom and hanging in the air can work as dynamic dampers with regard to the foundation slab. The seismic insulation system proposed is nothing more than information to be turned over in your mind. We do not discuss whether all proposed can be put into practice from the engineering and economic viewpoints [50, 51, 52].

In place of general conclusions to be made at the end of the book, I propose to look at some witty drawings evoked by the past and future of the earthquake-resistant construction (Figs. 129-138). Each drawing is expressive enough by itself but is furnished with detailed captions.

Fig. 129. Air-inflated bag with elastic walls that well insulates the building from earthquake waves; it is used in place of rigid foundation slab

Fig. 130. If the building is suspended on air balloons, the insulation from the earthquake element will be still better

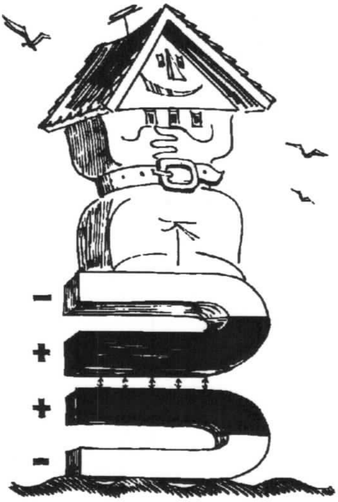


Fig. 131. Magnetic field force can be used for insulation from the earthquake element. If we could control gravity, this would not come amiss

Fig. 132. Good earthquake insulator can be a swimming pool filled with water or any other heavy fluid where the building rests afloat, being fully confident of its safety. This type of protection against earthquakes is quite feasible in our time

Fig. 133. A hovering building looks fantastic, but yet it is protected against earthquakes

Fig. 134. Use can be made of the tilting doll principle

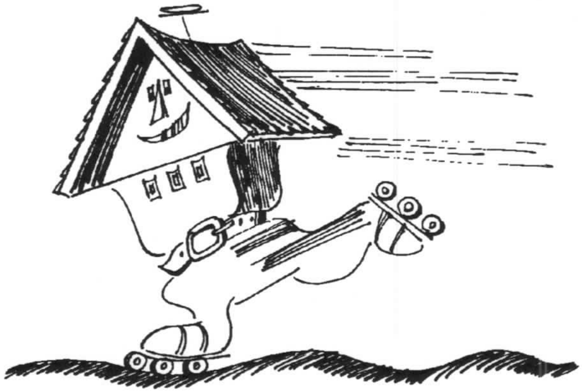


Fig. 135. The less the friction force between the building and ground, the better is protection against earthquakes

Fig. 136. Modern computers can control hydraulic legs so that no earth convulsion is conveyed to the building

Fig. 137. A huge-size rigid and bulky slab can protect the building against earthquakes; the larger the slab, the better is the protection

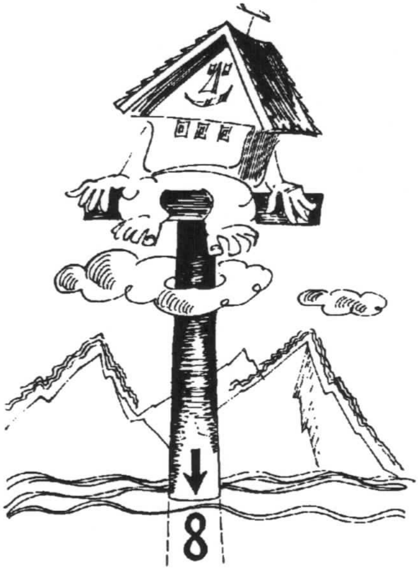


Fig. 138. Here you have another extreme compared to the previous drawing but the effect is the same. The deeper and more rigid is the pile, the better is seismic protection. In the former case the shaking was averaged over the ground surface, in the latter case—over the depth

Summing Up

That is all, my reader with a taste for knowledge, the book is completed. What a pity the book can not be appreciated by the author. However, I did my best to acquaint you with diverse and essential legacy of the past stamped in brick and stone, which was left by previous generations. The creations of ancient architects were deliberately analysed from positions of the modern theory of seismic stability. They proved to have much to study, and their heritage is of both educational and practical importance. The examples of ancient structures were readily used to demonstrate that the antiearthquake protection is a wide concept. It is far from being a simple increase in the concrete brand and amount of reinforcement used as many, even specialists, believe today. This protection is a whole system of measures ensuring the resistance of buildings to earthquakes and prolonging their service life.

I also wish the human history were considered by you, my venerable reader, not from the viewpoint of studying the number of rulers, towns they burnt and heads cut, but from the standpoint of great architects and skilled craftsmen thinking over the plans of buildings they designed and hewing stones to fit one another in masonry.

Whether I coped with the task is to be judged by you.

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