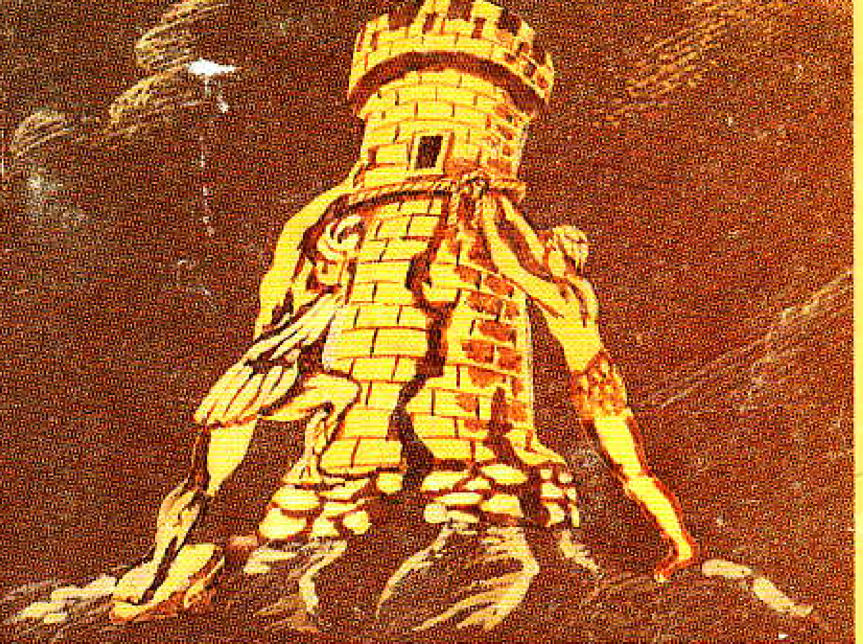

HISTORY of EARTHQUAKE RESISTANT CONSTRUCTION

from ANTIQUITY to OUR TIMES

B. Kirikov

B.A. Kirikov

HISTORY
of EARTHQUAKE
RESISTANT CONSTRUCTION

Some Pieces of Writing on the History of Earthquake Resistant Construction from Ancient to Our Days

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FOREWORD

Man has been exposed to the hardship of earthquakes since the ancient times and due to the impossibility to avoid them, he has learnt how to protect himself by improving his construction. Although the beginnings of Earthquake Engineering are tightly linked with the myth, the legend and the logical fear produced among people by catastrophic phenomena, nowadays we are able to say with certainty that this branch of science is perfectly consolidated and that, by its correct application, thousands of human lives are being and will be saved in the times to come.

This, naturally, has not always been the case. Engineers, architects and professionals in the construction field have managed to comprehend the origins and the effects of earthquakes by merely observing the damage produced on certain types of resistant design and construction of buildings and civil work. This process, which covers such varied fields as engineering seismology, seismic response of soils and structures, dynamic testing of materials and antiseismic regulations, started many years ago and it represented a clear example of transformation of purely phenomenological observations into analytical knowledge.

In this book, a translation into English from the Russian original, Dr. Kirikov makes a clear and simple excursion through history and the basic principles of earthquake resistant desing from the most ancient constructions to the present days. The exposition of pragmatic and typically engineering contents is eminently practical and it avoids both purely historical focusing and theoretical scientific approach.

The Asociación Española de Ingeniería Sísmica (AEIS) is pleased to present to the international community this interesting and necessary work whose publication coincides with the 10th World Conference of Earthquake Engineering (10WCEE) held in Spain. We would like to express our gratutude to the author, Boris A. Kirikov, for his generosity in giving us permission to publish the book and to the Instituto de Ciencias de la Construcción "Eduardo Torroja (ICCET) and the Fundación MAPFRE for deciding to support this project and offering us means to carry it out.

Rafael Blázquez
Director of Instituto de Ciencias de la Construcción
"Eduardo Torroja" (ICCET)
Director of 10WCEE
Steering Committee

Madrid, July 1992

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PREFACE

A scientific celebrity whose name I do not remember was asked how discoveries are made. The answer was that it is very easily done. There are things known to all people as impossible to be done, but there always exists an ignorant person who doesn't know that, and it is he who does make the discovery involved. My position is close to the all, since I am going to perform something that I know can't be done. In this book I am about to generalize the millennial experience of earthquake-resistive construction.

Because of the fairly limited space, the book restricts the author from including complete information about all earthquake-resistive structures from the ancient to the present-day time. More than that, it is hardly possible to collect all such information. However, there is another way of tackling this problem by fully describing the construction resistance to earthquakes in the historical aspect. To this end, the author has to tell the reader about the ideas and principles underlying the design of these diverse structures and illustrate them by examples. These principles of creating earthquake-resistive structures are really not so many. Most of those have been discovered in remote past and find their applications still now. Changes are made in the construction and building materials, in construction work techniques, and, finally, people vary, but the laws of nature remain unchanged with resultant unchanged principles of designing earthquake-resistive structures. I'll do my best to place enough emphasis upon these principles with a view to helping the constructor of today. To be brief, the author makes it his aim not so moderate to generalize the thousand-year experience in the field of earthquake-resistive construction and to illustrate the common regularities that have been obtained on the basis of this generalization.

Because of the unwilling application of earthquake-resistive construction by many nations, the need for comprehending its centuries-old experience exists for ages, but I saw as yet only two such attempts. There are a small but containing much information book, written by N.M. Bachinskyi dedicated to the ancient monuments of Central Asia, and a voluminous four-volume work of A.S. Bashkirov which deals with the earthquake-proof construction in ancient East, ancient Greece, Rome, and Black Sea coastal region colonies of Greece. These books were published more than fourty years ago in very small editions. References to these works follow in the text. To get them is practically impossible. By the way, the both authors were archaeologists, while this book is written from the standpoint of a builder.

At last, as I think, the subject of the book is of common interest. Some curious people wonder how those enigmatic earthquake-resistive buildings are constructed today and how they were built in the remote past. Others who live in earthquake regions must accept the fact that a major earthquake may occur at any moment and know what to do when it comes.

And so, I invite You, my dear reader, to the severe and mysterious world of earthquake-resistive structures in which each mistake involves sacrifices of priceless human lives and sufferings. Of course, I'll not be able to completely elucidate the subject, since it is too complicated and vast. However, even partial interpretation of the subject facts will be useful.

The present book is not historical in the usual conception, for which reason I'll not strictly follow the place and time frames of events, and we shall be free to move in area and time to better make our investigations.

I wish to express my sincere thanks to Luba Myachina who has kindly drawn the figures.

B. A. Kirikov

WHAT IS AN EARTHQUAKE-RESISTIVE BUILDING?

Some Words on What Will Not Be Discussed Here

This book is dedicated to true construction problems and therefore we shall not talk about the occurrence of earthquakes, propagation and path of seismic waves, and particularly about earthquake predictions. All these are examples of problems dealt with by the exploration seismology. The only thing I shall have to tell about herein to make the further reasonings clear is the motion of the ground under a structure during earthquake.

This motion is very complicated. Its true mathematical description can be performed only by the theory of random functions. In reality, during an earthquake, the ground motion under the building is concurrently caused by the various kinds of waves each of which has its own length, period of oscillation, amplitude, and velocity of travelling. As a result, all points of the ground under the structure foundation move differently, though sometimes in slightly different manners. In case of a next earthquake, this picture will not be repeated. It may be quite another. What will it be? It can be predicted only without going into details. Under such conditions of the so-called incomplete information on earthquakes, construction was carried out by the ancient builders and is practised by the present-day constructors. That is why, neither in the past, nor at the present, one should fail to refer to the experience gained in the earthquake-resistive construction of past years in order to comprehend it with a view to avoiding the mistakes made in the past.

The visible part of a building, that is, the part above ground, is called the superstructure. Below ground is the foundation, which may have any of a variety of forms (such as footings, walls, slabs, piles, caissons) and may cost as much as the superstructure. To design a foundation properly, the engineer in charge must have a detailed knowledge of the soil and geologic conditions at the site; this information is obtained by drilling holes into the ground and taking samples of the materials. This is because the soil properties influence much the earthquake characteristics and behaviour of the structure itself.

During the earthquake, the so-called process of interaction between the ground and the building takes place, which can aggravate or moderate the earthquake impact. How strange it may be, my impression is that *the ancient builders knew it and paid much attention to the preparation of the ground base for a structure. We shall discuss it in detail later.

More than that, to avoid unnecessary perplexity, it must be specified at once that the obsolete conception of earthquake magnitude will not be used. The matter is that the magnitude conception has been used to give you only a single measurement of a very complex phenomenon, - an earthquake. It was determined by the behaviour of non-seismic structures, and how can an earthquake magnitude be determined now in seismic regions all buildings in which must be of an earthquake-resistive type? In current practice, however, there is a developed network of seismometric stations for monitoring earthquakes by seismographs. The records produced by seismographs, called seismograms, are used in calculating the location and magnitude of an earthquake. From the current point of view, an earthquake must be characterized by its actual parameters such as the wave amplitude, period of oscillation, velocity of wave travel, etc. indicated by its records. Generally, everything that is needed for modern calculations and clear physical characteristics of the earthquake.

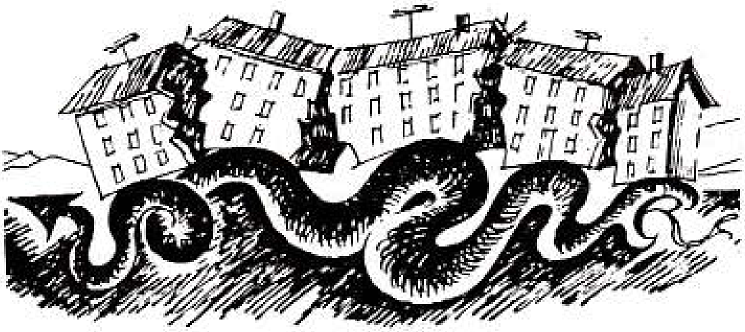

Fig. 1. Dragon-like Model of Earthquake Effects

Now, let us resort to some imagination to 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 shows the propagation velocity of travelling wave, its amplitude, prevailing periods, and all the other parameters. To make the picture complete, imagine a number of such dragons moving under the building.

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

The "multidragon" model of earthquake allows us to see without difficulty the chaos taking place under the structure during an earthquake, although being governed by a certain law at the same time. Individual points of the foundation move randomly, as it might seem. During a fairly severe earthquake, the building foundation is being drastically torn apart, compressed, twisted, bended, or undergoes all these actions simultaneously. The case is, that such a complicated motion of the structure foundation, generally unpredictable, must be controlled so that the building is saved. At once a question arises. Is it feasible to make buildings resist earthquake loads, having only approximate information about the phenomenon? The answer is yes, it is. This is proved true by the history of the earthquake-resistive construction. How is this done? We shall talk about it on the pages that follow. Strictly speaking, the book is dedicated to this problem. In that, it should be kept in mind that the present-day earthquake-resistive construction originates from its centuries-old history. In short, construction of earthquake-resistive buildings is a problem with many unknown quantities ranging from the features of the earthquake loads to the characteristics of the building involved, and one known stating that the human lives in the buildings in question must be saved in case of an earthquake.

Basic Principles of Earthquake-Resistive Construction

Prior to leaving for all continents and all times in search for seismic designs, let us inquire into what is an earthquake-resistive building? If treated in a narrow way, then an earthquake-resistive 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 being fully met, either due to some design mistakes, poor workmanship, or because of uncomplete knowledge of the phenomenon. Right are the people who live in an unreinforced brick building, or other hazardous structures, and feel it is better to take a chance on leaving the building than to stay inside, in particular when leaving quickly but cautiously, being on the alert for falling bricks, fallen electrical wiring, and other hazards. 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 mistakes in the building design, the materials will be durable, light and elastic, and the buildings will, respectively, become really resistant to earthquake loads and shocks, and on the first symptoms of an earthquake, people will be taking refuge indoors, rather than popping out outside. The bright future of the earthquake-resistive construction will set in, provided the human being will not degrade himself by constructing buildings worser than now.

This is the definition of an earthquake-resistive building made from the so-called humanistic point of view. The definition can be also 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, in some towns it is most profitable to carry out no anti-earthquake expensive work, provided human beings are prevented in some way from being killed, say, by earthquake prediction and people evacuation accordingly. If that is the case, it is better to construct a town anew after each severe earthquake in hundred or two hundred years. This is because bad earthquakes occur not so often, while the anti-earthquake measures are very costly.

I do not know how a more general definition of an earthquake resistant building can be formulated, but to my opinion, it can and must be done. May be, the theory of probability will help us in this case. For example, in short: "Earthquake resistant is a building which is probable to be damaged by an earthquake of an expected intensity, the damage probability not exceeding a certain magnitude within the whole of the building service life". The intuitive notion of an earthquake-resistive building simultaneously includes the specific features of the structure, safety of people, permissible level of damage, and economic figures.

According to the subject of this book, we shall dwell upon one feature of such a notion, as the earthquake-resistive building, namely, upon its structural features. To logically couple all the chapters of the book together, I'll formulate the fundamental principles of designing earthquake-resistive buildings. On the basis of these principles we shall see how these principles were met by ancient structures and study anti-earthquake designs used by different nations.

In compliance with the mysterious characteristic of earthquake-resistive structures, the number of these principles can be nothing else than seven. These are:

(1) The weights and stiffness (rigidity) of a structure must be uniformly and symmetrically distributed with regard to the planes of symmetry passing through the structure centre of gravity; the principle of symmetry.

(2) The proportionality requirements must be met by the building dimensions. In this case, the length and height of the building should not be too great; the principle of harmony.

(3) The structure must be as light, as practicable and have its centre of gravity as low as possible; the principle of antigravity.

(4) It is desirable that use is made of tough, light, elastic materials; the structures of these materials must have uniform properties; the principle of elasticity.

(5) The load-carrying elements of a structure must be coupled to one another to form closed contours both in the vertical and horizontal planes; the principle of closed contour.

(6) The foundations of earthquake-resistive structures must be firm, of enough depth. It is desirable that the foundations are based on yielding (ductile) beds or special substructures replacing weak soils to provide a uniform and firm ground base; the principle of solidity (fundamentality).

(7) Use should be made of contrivances reducing intensity of oscillation processes conveyed from the ground to the building; the principle of seismic (shock) insulation.

It should be said that the above-listed principles deserve the same attitude as any other principles, i.e. they must be observed, but not a bit completely. Certainly, very tall or asymmetric structures may be erected, but in this case, some additional measures should be taken to make them stand to earthquakes.

It is understood that the workmanship and quality involved by these principles should be excellent.

In short, these principles are called to prevent overstresses anywhere in the structure under loads. When an earthquake causes an abrupt concentration of stresses in some part of a building, this place is most liable to suffer ruin with resultant avalanche collapse of the entire structure. The engineering task in creating

Fig. 2. Suggested Poster for Regions of Possible Earthquakes

earthquake-resistive structures is to avoid overloads of building elements during an earthquake.

In the above-offered seven principles, I have attempted to generalize the centuries-old experience of the earthquake-resistive construction. Certainly, something else can be added to these principles, and I'll try to do this with progress in revealing the subject. As we shall see it further, all the above-mentioned principles will be found in the ancient structures withstanding earthquakes. You, however, must be ready to encounter all sorts of unexpected facts, since the structural implementation of these principles may show itself in most diverse forms.

So, the above-formulated principles of the earthquake-resistive construction are symptoms I invite you to search for in ancient structures to find out what antiearthquake measures have been taken in them. Of course, there are no drawings preserved, except a few, neither there are models of ancient, in particular, of most ancient structures. Frequently, such structures have been transformed into 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. Because of this, we can't know the thoughts of ancient architects creating their perfect structures, what design decisions were made by them to protect buildings against earthquakes, and how they generalized the experience of their predecessors. It may be that they did not treat seismic loads separately, and considered the whole set of external loads.

What to do? To my mind, the only way left is to consider the ancient structures from the present-day standpoint concerned with making buildings resistant to earthquakes, and make their analysis as dictated by the attitude of today. Certainly, there will be errors in our investigations. In one case, we shall attribute something not thought of by them to ancient builders. In other cases, we may not notice some structural hints utilized by the ancient builders to improve the earthquake resistance of their structures. To my mind, there is no other way to generalize the experience of centuries-old earthquake-resistive construction for the benefit of the present construction engineering than considering it from the present-day standpoint. Looking for signs of antiearthquake features of ancient structures, we should remember how many people have been killed, thousands and thousands more injured with destroying billions of dollars worth of property and causing incalculable social and economic disruption (Fig. 2). That is why, we must study the manifestation of earthquake forces to know better how to stand to them. We can do little to diminish earthquake hazards, but we can do much to reduce risks and thereby reduce losses.

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

How Are Buildings Made Earthquake-Resistive?

Prior to replying to this question, I'll try to preliminarily consider the following two problems. The first is somewhat straightforward and a bit primitive. How do earthquakes ruin buildings? By convention, there may be named two such methods. In the first one, a structure may fail due to non-uniform settlements of a weak foundation on a weak soil bed during an earthquake. Sometimes, the building may be weakened by non-uniform settlements due to other causes before. All these settlements result in overstresses in some parts or the whole of the building with subsequent damage to it. In the other method of earthquake destruction, the building is severely shaked, almost getting in resonance. This occurs when the natural oscillation period of the building is close to the prevailing period of ground shaking during the earthquake. In this case, stresses in the building's load-carrying structures caused by heavy strains overcome the ultimate strength of the materials and this also results in the destruction of the building. The challenge is almost clear now.

To erect an earthquake-resistive building, it must be protected against two things, i.e. against unequal settlements of the foundation which overstress the load-carrying structures of the building, and against almost resonant phenomena in it.

Now, there is one more question maybe of a philosophical kind. It asks whether the standpoint of ancient builders as to the construction of an earthquake-resistive building differs from the notion of today. I think they differ and essentially. A present-day builder may ask: "How can a non-seismic building be made an earthquake-resistive structure? What in this building is to be reinforced?" Very likely, the ancient builder couldn't ask such a question. As it may be judged by the ancient monuments of architecture, in his notion an earthquake-resistive building is in principle different from the conventional building. In it, the idea of providing resistance to earthquake loads and effects ought to penetrate everything from the proper treatment of the ground under the foundation to the top of the dome. Each stone of masonry seems to be thought about to place it better as dictated by its shape and structure, and secure it so that it can not be knocked out by earthquake shocks. In addition to tying the stones together, the mortar in the joints ought to protect the masonry from water penetration inside, which would otherwise cause gradual deterioration of the masonry. So, the hydraulic insulation of masonry is also a feature of seismic stability. The paving made around a building to prevent water from getting under it and into the subsoil under the foundation also represents a seismic stability feature. Sometimes, these as it may seem, minor structural elements have a major role in making a building resist to earthquake loads. Further, we shall talk about constructional antiseismic measures and I'll do my best to lay emphasis on what is of interest in the ancient structures. The problem of resistance to earthquakes was solved by a set of structural techniques together with other multipurpose measures. For example, a sand pad under the foundation may absorb earthquake shocks and serve for draining water away from the structure. So, after all digressions made, we can reply to the principal question of this section. How are the earthquake-resistive buildings constructed? Three essentially different approaches can find their applications in designing an earthquake-resistive building.

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

The second approach is as follows. It is known, the stronger and firmer the tie between the building and the ground shaked, the higher the seismic loads arising in the building, because the 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 diverse earthquake protection elements, such as sand strata, clay cushions, rush belts, sliding belts of metallic plates, rubber interlayers, balls, ellipsoids, air cushions, and springs. This approach existed in remote past and is actively developed in many countries today, as it makes it possible to erect cost-effective and reliable earthquake-resistive structures. We shall talk about the structural techniques of this approach mainly on the pages devoted to the present-day construction. Perhaps, it will be correct to call this trend a system of passive earthquake protection, in contrast to the third approach which uses systems of active earthquake protection.

According to the third approach, the buildings are furnished with some arrangements which change the dynamic abilities of the building when it gets in resonance and take it out of this state. In reality, this is the latest method of erecting earthquake-resistive buildings, since in this event, the building is equipped with various power units controlled by real-time computers processing the current information about the earthquake taking place to make the building respond to the 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 vary its rigidity, as if restructuring its structure with changing the period of its natural oscillations. However, in conventional buildings these changes are not under control and the period of natural oscillations may vary, approximating the period of ground earthquake-caused shaking with resultant resonance and possible collapse which was

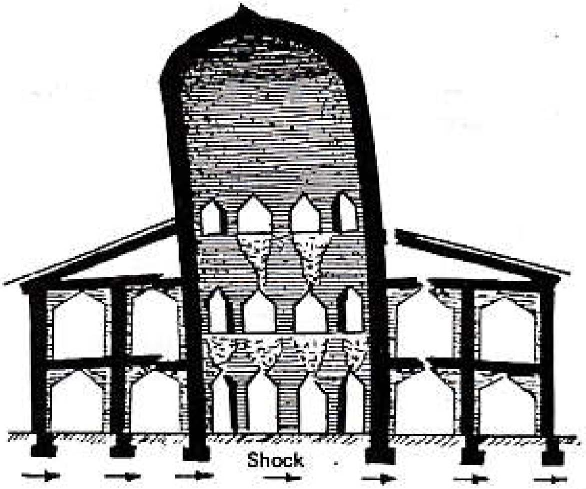

Fig. 3. Conversion of Buildings from Rigid to Ductile

frequently the case, or moving away from the period of shaking with abrupt drop of the earthquake loads. In the present-day computer-aided buildings, the system of active protection functions only so as to get out the building from resonance.

The following example shows how a building without any robotization is capable of restructuring its structure and adapting itself to effects of the earthquake. Recall the earthquake in the city of Ashkhabad, 1948 [1]. A mosque built of burnt brick in 1911 on strong lime mortar, in the best traditions of the Central Asia architecture, consisted of a central nonagon drum (Fig. 3), 33 m in height from the base to the dome top, and two else, far lower drums with arch ceilings situated in a concentric manner. These were ancillary buildings of the central structure. The whole of this structure in assembly was very stiff, i.e. the period of its natural oscillations was small. Evidently, the ground prevailing period of shaking caused by a near earthquake was also rather 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 whole structure was very stiff due to tying the central drum and the ancillary buildings into united whole. The struggle started with failure of the links between the central drum and one of the ancillary buildings. This can be seen in the Figure. Further, each part of the structure was fighting for its life separately, depending upon its structural features. The pillars of the ancillary building were sheared; thank Allah, they were not too strong. At once, the shaking energy transfer to the ancillary building from the ground dropped, since the ties between them were then merely due to friction. Here you have a prototype of the sliding belts we shall talk about later. The idea of such anticarthquake protection is suggested by the nature. The central drum behaved in a different way. Its pillars were too strong to be sheared. It then decided to sacrifice the integrity of its walls above the ground floor and first tiers of window apertures. Their fault resulted in cracks at 45 degrees to the horizon. Thus, vertical pillars of the dome had been formed, which were free to slide relative each other, being tied merely by friction. The stiffness of the central drum of the mosque abruptly decreased due to elimination of the ties whose function was performed by the arches above the windows. The central part remained undamaged too, since the dome was supported by a flexible, rather than stiff, structure having a large nonresonance period of natural oscillations. Such restructuring of the structural scheme of the mosque had saved its life, and it 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. It was easier for the ignorant persons involved. The mosque dome failed only after falling to the ground.

In order to finally understand the difference between the systems of passive and active anticarthquake protection, let us consider the so-called ideal examples of both systems. If a building were suspended to a balloon and lifted above the ground, it would be a system of passive anticarthquake protection. If that is the case, the building would be fully isolated from the ground shaking during an earthquake at all times.

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

It is understood, that with all the three abovementioned types of earthquake-resistive structures, their design should take into account the above-formulated principles of earthquake-resistive construction. A failure to take into consideration the requirements for the structure symmetry with a building erected on shock-wave absorbers will result in such torsion torques that some building elements will be over- and some underloaded. The overloaded elements will fail with subsequent destruction of the entire system of shock-wave absorption. Even the helicopter-building needs the structural symmetry, not to mention the requirement for lightening the structure.

So, the first chapter, being theoretical and thus most tedious, has acquainted, I hope, the reader with the field of earthquake-resistive structures. Herein the class of problems that will be dealt with in the chapters that follow has been outlined. The task of the book has been set, it only remains to solve it.

WISDOM OF MOST ANCIENT BUILDERS

At Time Immemorial

Let us start with most ancient structures whose purpose and construction time are difficult to date. These are megalithic single-type structures which can be met in areas from Japan to France and Great Britain. Their existence sets one thinking of destruction of ancient civilizations, persons from other planets, and the like. The talk is not about this now. The talk is about the fact that many of them situated in seismic regions have withstood many earthquakes in the course of their life having a few thousands of years and remain well preserved. One can hardly take it in, that these structures built of supergigantic flat stones were created by people wearing animals' skins. It is clear that they were erected by an organized society with their own engineers and even academicians to our notion. Those specialists were the men who developed the structure itself and the relevant techniques of construction work. We shall never know whether they thought of the earthquake resistance of those structures, or not. Perhaps, a machine of time, if invented, will help us know it. The fact analysis, however, shows that they thought of it. An example is a two-tier dolmen (Fig. 4) erected in a very harmonic manner near the settlement of Gorikdi, Azerbaijan, [2]. It is made of ten stone plates (slabs) thoroughly fitted to one another. The slabs are approximately equal in thickness. It is about square when viewed from its top. Practically, the dolmen meets all principles of

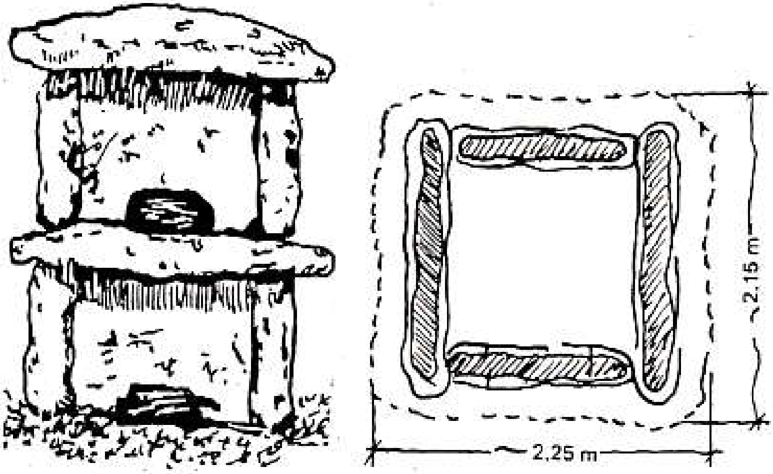

Fig. 4. Two-Tier Dolmen Resistant to Earthquake

earthquake-resistance construction. Its stiffnesses and weights are distributed uniformly and symmetrically. The bearing joint places have ductile hinges. When a certain level of displacement is exceeded, the stone plates butt against each other to form ties limiting the amplitude of system shaking. The structure first works in a ductile manner and then as a stiff nonlinear structure. Many other scientific terms can be mentioned that were unknown to the builders of this most ancient dolmen. From the modern standpoint, 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.

Now, does the question whether the ancient builders, who erected their megalithic monuments, thought of resistance to earthquakes or not, still remain? In all probability, they did not. Most likely, however, they obeyed some their own principles to provide the general integrity of the structure. It seems to me, they evaluated at once the resultant effect, without dividing the affecting action into wind, snow, earthquake, and so on effects, as we do.

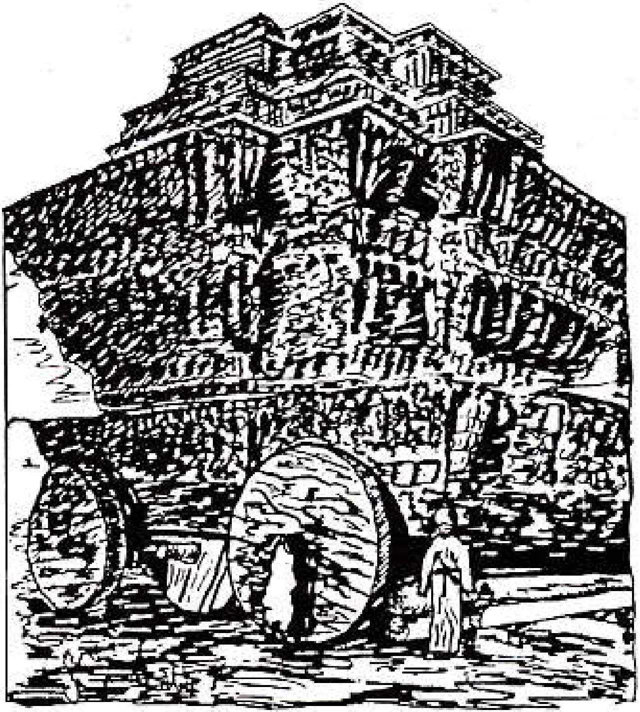

Fig. 5. Ancient Indian Wheeled Temple

Clay models [3] of worship wheeled structures, even three-storied, found in excavations are another example. Ancient Indian wheeled temples (Fig. 5) have been also mentioned [4]. It is known that wheeled houses existed which accompanied ancient sovereigns during their campaigns. Certainly, this is far from being an ancient invention of an antiearthquake-protection device in the form of wheels, though a wheeled temple is certainly an earthquake-resistive structure. We shall face such a 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 seismic protection, regardless of what the ancient architects thought of.

After the ancient builders, we shall move on to the most ancient civilizations. Although, it already follows from the above-said that structures were erected in remote past quite intelligently. Thus, the foundations for erecting monumental structures have been laid and we shall talk further mainly about them.

Whereon Did the Towers of Babel Stand

Let us talk now about the construction art in the ancient states existed already in the 4th millennium B.C. The first to found city states in the Tigris and Euphrates fertile valleys were the Sumerians. As the first historically attested civilization, they are credited with the invention of cuneiform writing, the sexagesimal system of mathematics, and the socio-political institution of the city-state with bureaucracies, legal codes, division of labour, and a money economy. Their art, literature, and theology had a profound cultural and religious influence on the rest of Mesopotamia and beyond [5]. In Greek, Mesopotamia means "between the rivers".

The Sumerians were acquainted with many sciences and were skillful farmers, architects, weavers, potters, and jewellers.

The construction materials used in the Sumerian states were dependent upon the natural conditions. The unwooded plain had no stones and wood materials, but was rich in silt and clay, and there was much bitumen. Naturally, bricks were widely used there. First, those were hand-prepared one-side convex adobe bricks later substituted for by frame-made bricks. At the beginning of the 3rd millennium B.C. wide applications were found by burnt bricks. There was wood, but very little, and it was very costly. When an owner of a house was leaving his house, he took the wooden door with him as a piece of valuables.

From our point of view, of the interest is the study of earthquake-resistance techniques, and the wall structure developed under those conditions of the materials then available. The major bulk of the walls faced with burnt bricks was of adobe bricks bonded by clay mortar and bitumen. Each 5-13 layers of bricks were placed on a rush mat impregnated with bitumen to

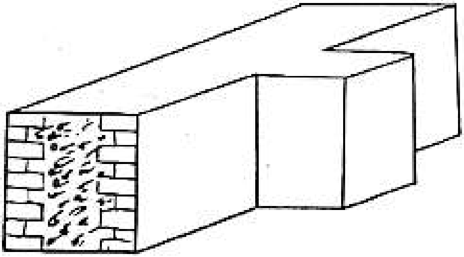

Fig. 6. Most Ancient Earthquake-Resistive Masonry

protect the masonry from moisture and soil salts. The lime mortar found its use far later in the middle of the 1st millennium B.C. Burnt bricks were mainly used for facing walls [6].

It is clear that such a wall structure was elastoplastic, rather than stiff. These properties were imparted to the wall by its central part composed of soft bricks bonded by mortar of clay and bitumen. Ground shaking caused by an earthquake and transmitted to such a massive wall was absorbed due to the wall elasticity and ductility. The general stability of the building wall was supported by transverse walls and counterforts which had been used already then (Fig. 6).

This is the first structure of an earthquake-resistive wall in our system of chronology which was used more than 5000 years ago. In addition to earthquake effects such a wall is capable of standing unequal settlements of the ground. This design of a massive wall composed of a rigid facing and a soft core would be used further, up to now. Changes would be made in the materials and building structure, while the principle of the three-layer wall would remain unchanged.

Another effective earthquake-resistive provision that had been utilized already at that time was represented by the construction of buildings on the grand scale, such as temples and palaces on huge very deep stages (platforms). These provisions will be encountered further in many ancient states from China, Persia, Egypt to Mexico. Ziggurat in the city of Ur built at the end of the 3rd millennium B.C. is a rectangular staged

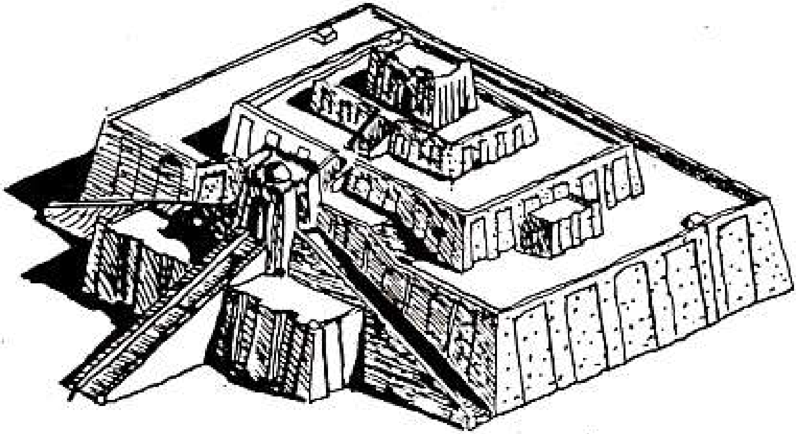

Fig. 7. Ziggurat, the 3rd Millennium B.C.

temple. The stage is 43x65 m in area and 15 m in height above the ground surface. It is built of mud brick and faced with baked brick laid in bitumen. For the view of this ziggurat (or better zikkurrat), see Fig. 7. In reality, it was a man-made mound. Note, the ideal shape of the mound from the seismic standpoint. Note, in particular, the uniform and symmetric layout of masses and lowered position of the centre of gravity of the whole of the structure.

How do the stages like those under the ziggurat in Ur work? The dimensions of a surface earthquake wave are commensurable with the dimensions of the stage, and the task of the large stiff stage is to smooth out the wave, and the structure thus becomes subjected to an averaged seismic ground motion free from abrupt peaks.

The stiff stages were used under temples, palaces, and even under entire towns. The stages had more than one function; for example, they could be used for defence purposes, to deeply impress religious persons or citizens when they approached the temple or palace, and at the same time to form a reliable foundation under the structure, and finally to perform anti-earthquake functions. It should be noted, that in Mesopotamia stages under the structures were made out

Romans (after sinking through some alluvial deposits) based their foundations on solid rock, Mesopotamians could not do so, since loose rocks there lied very deeply. Being aware of the importance of good foundations for earthquake-resistive buildings, they created gigantic stages for the erection of structures on weak grounds.

Later, in the 1st millennium B.C. still greater stages were constructed by the architects in Assyria who had borrowed from the construction experience of Sumerians. The city of Dur-Sharrukin, the residence of king Sargon II (721-705 B.C.), was built only in six years (712-707 B.C.). Although the walls were built of mud brick, they were carried by a foundation of large stone blocks. Counterfort towers were built at intervals of about 20 m. The most interesting is the fact that the citadel in which the temples, houses of courtiers, and the palace of Sargon were situated, was erected on a stage about 100 000 sq metres in area and 14 metres in height. The stage was built of mud brick and faced with huge stones up to 14 tons in weight [7]. Like in Mesopotamia two millennia before, wide use was made in that city of various vaults about which we shall talk later.

After talking about ancient Sumer in the Euphrates valley, it is naturally to recall another similar civilization of brick in the Indus valley. It was the Harappa civilization which occupied an area greater than the regions of the Mesopotamian and Egyptian civilizations. It is difficult to find out when that civilization arose and developed, but its first period was from 3200 to 2400 B.C. [7]. There is little to be said about the antiearthquake protection techniques used by that little-studied civilization discovered during the second half of the last century. We are astonished, however, by the high level of that time construction culture and city improvements characteristic of that civilization. Excavations have recovered wide straight streets built with multistorey houses of baked brick. At that prehistoric time such a high degree of building typification and standardization could be seen nowhere except for the Harappa civilization: similar planning of cities, standard houses of baked brick, the common unit cities, standard houses of baked brick, the common unit of weight, and typical mass production potteries. The used bricks were of good quality. It is enough to say that later its baked bricks were looted to serve as ballast on a railway line. That civilization also erected large man-made stages of brick.

One of the twin capitals of the Indus civilization, named Mohenjo-Daro, on the west bank of the Indus southwest of Harappa was a city covering approximately a square mile. It was laid out on a grid plan, the oldest recorded. The larger blocks, separated by broad streets with elaborate drains, were subdivided and closely built over in baked brick. A block in the middle of the west side stood higher than the rest, forming a 35 ft citadel. It stood on a stage from 9 to 15 m high, 190 m wide, and 380 m long. It was reinforced by double walls 12 m thick at the base and 11 m high. Within it an assembly hall, ´college´, great bath and granary were excavated. The highest point is covered by a Buddhist stupa of much later date. Excavation could not reach the lowest levels of the site owing to the high watertable. Recent drilling has brought up cultural material from as much as 39 ft below the modern plain surface, with the mounds rising 35 ft above this level. Much of this depth is made up of flood deposits, which many times overwhelmed the city. The highest levels showed a distinct cultural decline, and the final collapse is marked by groups of unburied skeletons.

Such floods occurred in that site several times. Cities were ruined and restored. At least, every hundred years the Mohenjo-Daro region was overwhelmed by a mud-water sea. That happened more than five times. Gradually, this led to the failure of the Harappa civilization [6].

Now, we shall dwell upon the less ancient Minoan Crete civilization somewhat different from the above-discussed two. This civilization is better studied. In this case more ancient monuments have been excavated and described.

The Aegean sea island areas, including the island of Crete, feature high seismic activity. Earthquakes are frequent in this region with resultant gaining of much experience in earthquake-resistive construction still at that times. In this connection there existed the worship of inextinguishable fire dedicated to the god -'earth shaker' that was to be continually gratified [8], while the live fire was constantly reminding the people about the danger they were in.

In the above-mentioned civilizations of brick the anti-earthquake techniques were evolved on the basis of intuition. Examples are bonds of brick masonry, thickening walls at the footing for better stability, use of counterforts. A system and knowledge of the structure work fundamentals can be traced in the most ancient "Aegean" and later Greek architecture associated with it, which allowed the ancient builders to develop specific structural techniques for erecting buildings resistant to earthquake loads. It is well seen from the analysis of the Greek world structure that, though the basic construction material was represented by stone known for its hardness and brittleness, the builders tried to lend the ductility and elasticity properties to their stone structures and to integrate all load-carrying structures into a common system tied in all directions.

Much of our knowledge of Crete at this time comes from the great palace of Knossos (Cnossus) related to the Middle Minoan (2100-1600 B.C.) of the Aegean culture on Crete. Knossos was the palace of the powerful legendary King Minos who gave his name - Minoan - to the Cretan civilization. Its excavation was the life's work of Sir Arthur Evans. The palace excavated for the ruins of large ensemble, 24 000 sq metres in area [8]. Some earthquake-resistance improvements used in that palace are as follows. Natural gypsum was the major building material of which large stone blocks were made. From the seismic standpoint this is a poor material, too brittle and weak. All this was well known to the builders of Knossos and they tried to impart the required abilities to the wall masonry. First of all they thoroughly made the stone blocks fit to one another to provide thus the maximum strength of the entire wall. No mortar was used, the stone blocks being connected by wooden dowels which made the masonry somewhat ductile. The thick outside walls were faced with edgewise placed plates which

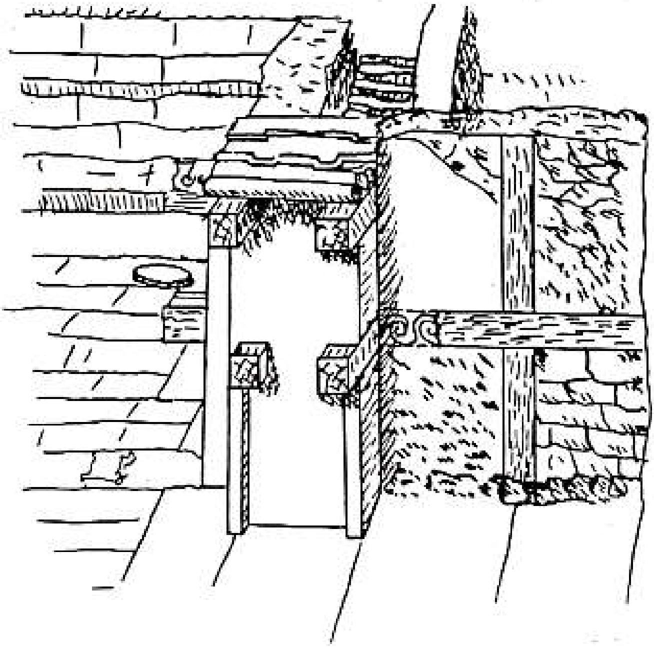

Fig. 8. Reinforcing Stone Masonry with Wooden Beams. Knossos Palace, the 15th Century B.C.

were alternated so that some of them were placed parallel with the wall, and some - crosswise. The voidage formed between the plates was well packed with building rubbish. Of the greatest interest was the fact that the wall masonry was thoroughly reinforced in the vertical and horizontal directions with wooden beams (Fig. 8). This made the wall monolithic and elastic so that it worked as a united whole. Exactly in the same manner, stone blocks and wooden beams were utilized to tie walls to each other to form a united closed system making the building earthquake resistant. More than that, much wood used in the stone masonry cut down its weight.

The columns used in Knossos were also of interest. They were wider at the top and narrower at the foot, and they looked unusually. However, good thinking shows that this is correct. The beams are supported by the column top end, and the log butt end forms the column capital suitable for the bearing parts of the beams. A hinge is readily formed at the column base which makes the column work so that it can be compressed rather than bent.

Much emphases were laid on the island of Crete on preparation of the ground bedding for the structure. Even minute irregularities of the ground bedding were thoroughly levelled or cut away. Depressions and crevices were filled by building materials. Level grounds in the form of steps were created on the hillsides on which the structures were erected. A sand-gravel layer was formed between the ground bedding and the structure foundation. One of its functions was to uniformly distribute the foundation load and to damp earthquake shocks.

The buildings of Knossos had at least three storeys. As a rule, the ground floor was built deeper in the ground and had a greater number of longitudinal and transverse walls tied to one another than the upper storeys. All this provided a strong and reliable base for the upper storeys [8].

Knossos was very enigmatic. For example, why were there no defence walls around it? One more enigma remains unsolved. It follows from the excavations that the bedrooms were as a rule on the ground floors. Why so? One of the authors [9] even maintains that the Cretan citizens took shelter from earthquakes underground, since the amplitude of surface waves abruptly decreases with depth. All this is correct, the earthquake effects really decrease with depth. If that is the case, however, the ceiling above the ground floor must be strong enough to withstand loads caused by the collapsed upper storeys.

Knossos is situated in the most active seismic zone of Crete. Accordingly, it was ruined by earthquakes and eruptions that were often in that region. The palace was not finally destroyed until the 14th or the early 13th century B.C. Apparently, those antiearthquake improvements that had been used and talked about herein were not sufficient to save the palace till our days. Naturally, since the palace flexibility and monolithic character were ensured by such a short-lived material as wood.

Well, we have studied in a short way the ancient civilizations and shortly acquainted ourselves with their construction techniques, and it is clear that three or four millennia ago there existed a problem of earthquake-resistive construction to start the active struggle of people against earthquake effects which continues still now. The foundations of such construction have been laid at that time.

Let us continue our study of the ancient Greek world.

Seismic Stability of the Trojan Horse

Let us visit legendary Troy situated on the shore of the Aegean Sea and praised in Homer's Iliad. The excavations carried out by Schliemann and Dorpfeld have shown that the Trojan mound, the mound of Hissarlik, also known to the Greeks as Ilion, contains at least nine cities of Troy. Troy I arose two millennia before the second Troy described by Homer, between the 4th and 3rd millennia B.C. The next cities of Troy formed successive cultural layers above each other. That city of Troy seized by Greeks with the aid of a war ruse was Troy VII [6]. The ruse was represented by a Wooden Horse also called Trojan Horse. The building of a large Wooden horse, inside which many Greeks were to be hidden, was advised by Odysseus and built by Epeus. To persuade the Trojans to allow the horse inside the walls of Troy, Sinon, a Greek who had let himself be captured for that purpose, told the Trojans that it was an offering to Athena. In spite of the warning of Cassandra and Laocoon, who said, "I fear the Greeks even when they bring gifts," King Priam was deceived by Sinon and allowed the horse to be brought inside Troy. At night, the Greeks hidden within the horse were let out by Sinon, the gates of Troy were opened, and all of the Greeks hidden behind the island of Tenedos returned, entered the city, and sacked it. So Troy VII fell [6].

Fig. 9. Aseismic Trojan Horse

From our standpoint, Trojan Horse (Fig. 9) was an ideal earthquake-resistant structure that met all the antiearthquake protection principles stated above. The dimensions were moderate. The Horse housed Greek soldiers with spears and was about 2- or 3-storey building in size. Its construction was symmetric. It was made of wood, an elastic and light material. More than that, it was well insulated from earthquake loads by means of the wheels it stood on.

The structures of Troy itself lacked such an ideal resistance to earthquakes, since it was built of other materials and had different dimensions.

We shall consider Troy VI established by Greek tribes. That city was prospering by the Middle of the 2nd millennium B.C. In size it was far larger than the city of Troy VII. It was a wealthy city with good buildings. Nevertheless, Troy VI was ruined by an earthquake in the 14th century B.C. The earthquake-resistive improvements that were used then were insufficient. Those were as follows.

Shown by excavations, Troy VI extended to *5* acres with elaborate walls, gates, towers, and auxiliary accommodations built of large stone blocks well fitted to one another, laid in uniform horizontal rows to form a perfect system of defence. Some blocks weighed up to 2-3 tons. Some long stones were placed across a wall, as the so-called "bondstone" to add to the wall strength. The walls, towers, buildings had foundations laid of especially large blocks, deep on the rock. In case of uneven rock surface, a special bed was cut for the foundation. To improve stability, the walls and towers had a large external rake. All those were improvements of the earthquake-resistive masonry devised at that time.

To the point, somewhat different structure of earthquake-resistive walls was used in the ancient "prehistoric" Troy. To impart ductility and monolithic properties to a wall, it was made combined of wood, clay and stone [8].

The architecture ensemble of most interest at that time was represented by Mycenae related to continental Greece. The golden age of the city of Mycenae fell on the 12th-10th centuries B.C. At that time Greece on

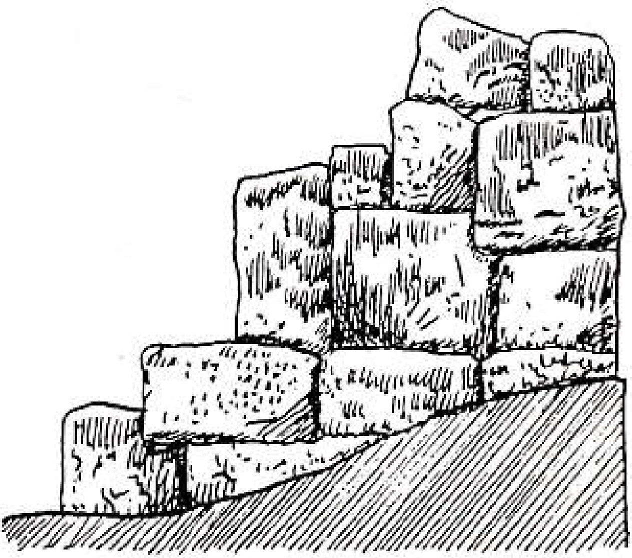

Fig. 10. Cyclopean Masonry of Ancient Greece. Mycenae

the mainland was divided into small tribal alliances that were at daggers drawn. The country was restless. As a result, many well fortified settlements were erected. One of such settlements was represented by Mycenae. Situated nearby were Tiryns, Argos, and others also well fortified.

The defence structures of Mycenae were situated on the crest of a hill. There were unassailable cliffs on two sides, and only on the other two sides where the rock is gradually sloping towards the valley, massive unassailable walls rose.

The walls were characterized by the use of very large close-fitting irregular stones. The ancient Greeks 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, worked into place, and laid on each other. Bonded to one another by gravity, the stone blocks firmly held one another (Fig. 10). In places of importance, to reinforce the masonry still

Fig. 11. Corbeled Triangle of Lion Gate, Mycenae, the 16th Century B.C.

more and prevent the stone blocks from sliding in case of shaking, wooden vertical dowels were used along the horisontal seams. The dowels were inserted in the holes provided in the upper and lower blocks [8].

The city of Mycenae was entered by the monumental Lion Gate (Fig. 11) which stands more than 30 centuries till our days. The gate was built of four huge stone blocks to form a 3 by 3 m aperture. One block is used as a threshold. Two other vertical blocks support the fourth stone block spanning the passageway. This mammoth stone block is 4.5 m long and weighs 20 tons [6]. The construction of this gate is such that the weight of the masonry above is not transmitted to their fourth block, since the above-gate masonry forms the so-called false (corbel) arch built by uniformly advancing the courses from each side until they meet at the midpoint. The formed void was then closed with triangle stones having depictured lions. Such a structure reducing loads above passageways made in walls was called an unloading (corbeled) system. Further, we shall frequently encounter different structures of unloading systems.

The construction of this gate, when looked at, fills you with admiration for how much ancient people knew about the work of a material in a structure. They obviously were well aware of that the stone perfectly stood compression and could not withstand bending loads. That is why, they provided an unloading triangle above the girder under a bending load in which the stone in the lower zone was subjected to extension. More than that, since the bending moment at the centre of the girder is at its maximum, the centre portion of the girder was bulge-made. To add still more to the unloading of the central portion of the girder, the builders have weighted down its ends by the stone masonry of the false arch, 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. Looking at the gate, it comes to mind that such a cyclopean structure of stone could not be better designed even by the modern engineer using the most advanced theory of structure design.

The above-said does not yet exhaust our interest in the structures excavated in Mycenae. More was still learned from others in the lower town that have survived. Later members of the royal family were buried in the great tholos tombs in the form of a beehive-shaped chamber built of stone and roofed by corbeling. These are of interest in their construction. The tholos tombs were wrongly attributed to individuals in the Homeric legends, Atreus, Clytemnestra, etc. Let us talk about the tomb of Atreus (the 14th century B.C.) known as the 'Treasury of Atreus'. The construction of this tomb was brought to perfection. It had a number of predecessors, but due to some blunders many of the ancient tombs failed, while the tomb of Atreus stands already more than 35 centuries.

The burial chamber of the tomb is 13.2 m high and its circular outline is 14.5 m in diameter (Fig. 12). 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.

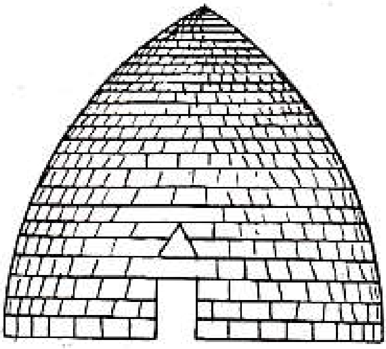

Fig. 12. Lancet Dome and Corbeled Triangle of Tomb of Atreus, Mycenae, the 14th Century B.C.

The largest blocks are laid in the lower portion of the wall, the blocks becoming smaller and the wall - thinner with height. Referring to the figure, the dome profile is lancet-shaped. It turns out, that such a dome configuration well satisfies the antiseismic requirements. This will be discussed in dealing with the Mussulman mausoleums. The massive dome has two door openings, high and low, both spanned by girders above which unloading triangles are formed in the manner abovespoken. Strictly speaking, the whole dome of the tomb of Atreus was laid in the corbel dome manner, i.e. by projecting all blocks of each masonry course progressively towards the centre with height. The whole of the massive dome is situated underground to provide compressing the dome from outside. The material is the local siliceous limestone of high density [6].

As seen from the above-said, the construction of the tomb of Atreus meets the major principles of the earthquake-resistive construction: good proportion, axial symmetry, lancet-shaped dome (lightened with height), elimination of stress concentrations at the openings provided in the dome, strong material with possible displacement along the horizontal seams of the dry-laid masonry. This is confirmed by the fact that the tomb of Atreus exists in the course of 35 centuries.

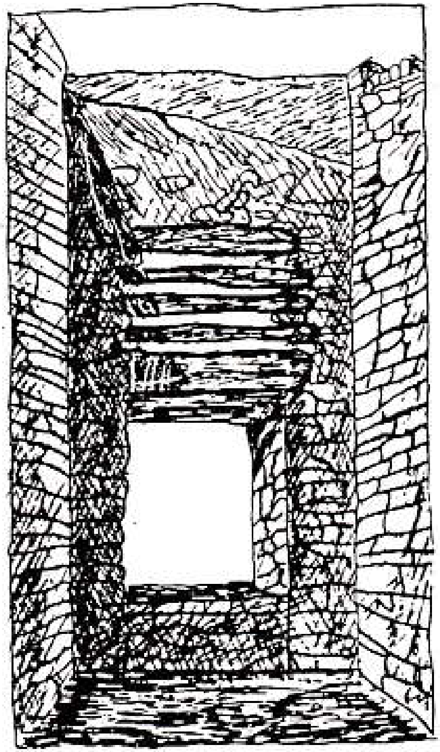

Fig. 13. Unloading System above Entrance to Tomb in Menida

The study of ancient structures shows that the builders of the past took care to eliminate stress concentrations in their structures. There are two more examples. An ingenious witty unloading system is found above a wide door opening in the domical tomb in Menida. As a result, the girders spanning the door opening carry no overload, except their own weight. The construction of the system is as follows. Heavy monolithic girders are placed above the door opening in the thick wall, and four rows of thin plates are laid above them with narrow clearances between the plates (Fig. 13). One can see, that no overload is exerted on the girder.

Some more words must be said about the above-mentioned fortified citadel of Tiryns, the acropolis of which with the walls and a new palace was completed in the 14th-13th centuries, B.C. More impressive than the palace are the defensive structures having massive walls of cyclopean masonry, from 8 to 17 m thick, containing corbeled galleries. There is much to speak of in studying the structures of Tiryns, but we shall consider only one of the structural elements of that city. The matter is that the defensive structures of the city have aseismic seams dividing complicated or very long structures into simple elements, so that these seams provide their independent deformation. The towers are not tied to the wall by common masonry. They are separated by as if a slide seam that allows the wall and the tower to shake independently to eliminate force concentrations which otherwise would occur in these places during earthquakes or in case of unequal settlement of the wall and tower. This is also convenient from the defence point of view. If the tower were destroyed by an enemy, then, when collapsing, the tower will not affect the walls. The wavy wall of defence is also divided into simple elements. There is also a seam between the wall and the palace building [8]. In this case, the structures of intricate configuration are intentionally divided in a professional manner into independent simple elements that can move independently, and this is required under earthquake-hazard conditions to reduce stress concentrations.

It can be said now, that the ancient builders were at their best in providing nearly all the principles imparting buildings the abilities of standing to earthquakes that were stated in Chapter 1, except maybe seismic insulation which was featured only by Trojan Horse and Indian temple. It is just the time to go on an excursion to the pyramids and temples of Egypt.

The Law of Gravitation in Place of Cement

The people of Ancient Egypt formed one of the earliest civilizations in the world and have left more archaeological remains than any other ancient society. Thanks to the dry Egyptian climate, many of these have survived, providing evidence of daily life and also of the high standard of craftsmanship.

The narrow fertile strip of land on each side of the River Nile was called the 'Black Earth' by the Ancient Egyptians. On either side of the 'Black Earth' stretching for about one thousand kilometres is the desert which was called the 'Red Earth'. The fertile Black Earth was formed by the great floods which take place each July and October. The floodwaters carry mud and silt which cover the fields and renew their fertility. It is not surprising that early man took advantage of this great richness and made the Nile valley a centre of agriculture from very early times.

The Ancient Egyptians believed very firmly in a life after death. Indeed, if it were not for this, we would know much less about them, for most of our knowledge is based on the many tomb paintings showing scenes of everyday life.

The Egyptians also built tombs, the greatest of which were the pyramids, the tombs of pharaohs. These contained the dead ruler's mummy and possessions: furniture, precious objects, and jewellery put there to ensure a comfortable existence for their owner in the afterlife.

A more thorough analysis of enormously massive and heavy structures in Egypt may lead to a conclusion that they are conflicting with one of the principles of earthquake-resistive construction, i.e. the requirement to reduce the structure's weight.

It brings about an impression that this principle is not only ignored in these structures, but they are specially made as heavy and massive as possible. They have no internal voids or light filling materials used to reduce the weight of a pyramid or a temple. These structures, however, continue to exist during several millennia, in an earthquake-hazard zone. Why so? Maybe the weight is not to be reduced? It is to be reduced, and everything is correct with the weight. Other laws become effective with vastly heavy structures. Most important in this event 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 the

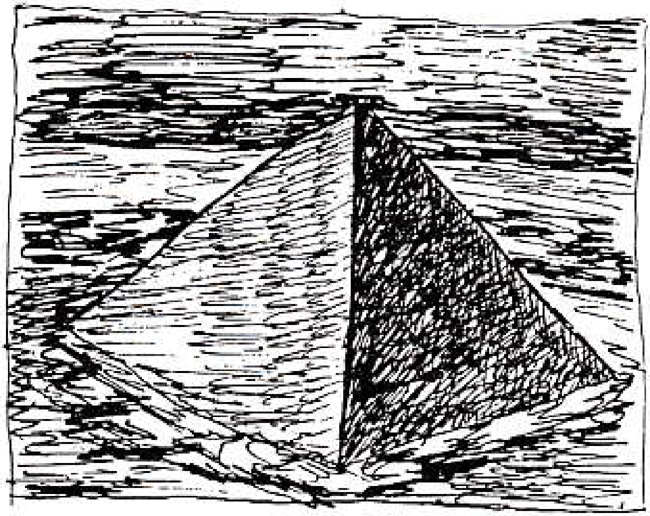

Fig. 14. Geometrical Harmony of Great Pyramid of Cheops

earthquake and the superheavy structure is not imparted the displacements and accelerations, as the case might be with a light building situated in the same site. Physically it can be seen from the snake-like dragon model offered above. The dragon has but not enough force to badly shake a superheavy structure as the ground deforms under it.

Superheavy structures have survived not only in Egypt. Cyclopean dolmens more ancient than the Egyptian pyramids are surviving in the Caucasus known for its high seismicity. In Greece either, the tomb of Atreus with the central room having a corbel lancet-shaped dome has a side chamber spanned by only two stone slabs of which one, 8 by 5 by 1.2 m in size, weighs more than 100 tons. These heavy structures have well survived too [6].

So, creation of superheavy structures is a possible trend in erecting earthquake-resistive structures. Most of the architects, however, preferred and prefer now to erect light buildings which is a more simple and cost-effective way.

As the next step, let us consider some structures of Egypt from the standpoint of the weight principle used in them, and make an analysis of how the own weight of a structure supports its integrity and monolithic nature in place of cement mortar. Let some talk be made about the pyramids. These structures are so harmonious that there is no need of speaking about special seismic protection. All that is of genius, is simple. The pyramids are ideal in shape from the standpoint of resisting earthquake loads. They feature all principles above-mentioned, except for the weight reduction principle. As said before, the latter principle of using weight against earthquake effects is specifically satisfied by the Egyptian structures. An example is the largest and most famous pyramid erected by pharaoh Cheops (Fig. 14) in the 26th century B.C., at the time of the Old Kingdom. This is the most ancient and large pyramid in the Giza. The Great Pyramid of Cheops measured 756 ft a side with an original height of 481 ft. It was laid out with remarkable accuracy, its sides are, of the same length to within 8 ins and aligned on the cardinal points to within 1/10 of a degree. 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. Except the burial chamber and galleries (Fig. 15), the internal masonry is solid. On the outside, the pyramid is faced with plates of ground limestone [6]. The stone blocks are laid without mortar which is unnecessary because of their size and weight. They only must be well fitted to each other and this will make the masonry strong and uniform. Mortar is used only when the masonry is laid of small stones, bricks of similar materials. So an analysis of the pyramid construction from the standpoint of earthquake-resistance principles shows the following: the structure mass and rigidness are distributed uniformly, the symmetry requirements are met, the centre of gravity is lowered, the height, width and length magnitudes are commensurable, and the masonry is strong. The pyramid body is a uniform mass, therefore, nothing can fail in it. There are no ceilings and domes that might collapse. It turns out that the earthquake resistance of the Egyptian pyramid is normal, and there is no need to discuss it in detail.

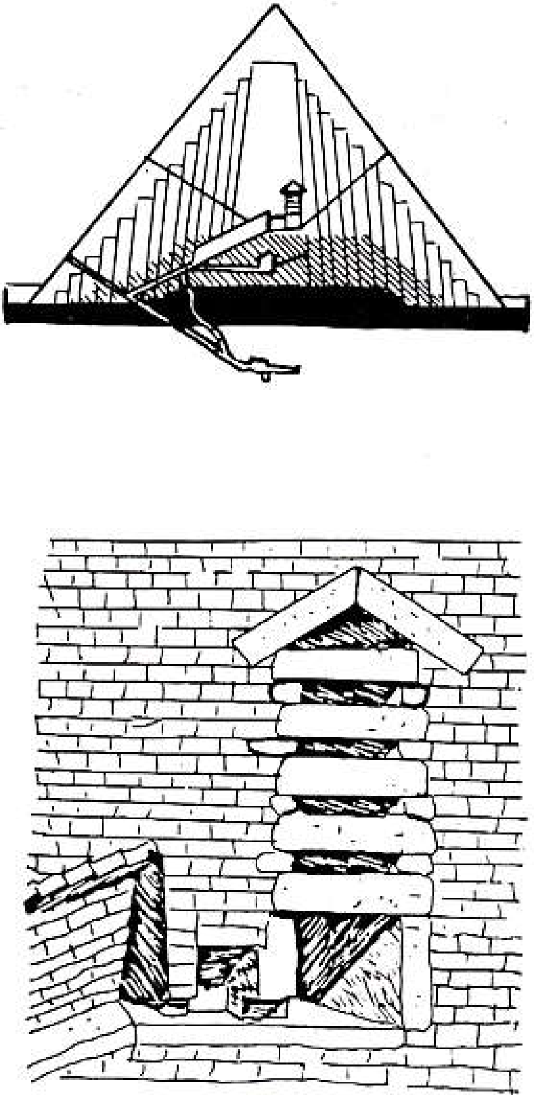

Fig. 15. Unloading System of Burial Chamber and Galleries of Great Pyramid of Cheops

The only thing left to be discussed in connection with the pyramids is the burial chamber (Fig. 15) as the principal element of pyramids after which we shall proceed to considering the Egyptian temples. Several duplicated slabs span the burial chamber, and the top slabs are leaned on each other to form an unloading system. These are the most important slabs taking the load. The bending momentum exerted on them is reduced and they partially work in compression. This is a simplified vault.

The largest and most magnificent temples were erected in Egypt during the years of the New Kingdom (the 16th-11th centuries B.C.). We shall not dwell upon each Egyptian temple and the merits of its architecture. Our task is to discuss the structural techniques that were used in them to make them stand earthquake loads.

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 having a vague idea of the intricacies of soil mechanics which we can not yet comprehend. Maybe the Egyptians understood the soil mechanics, better than we do. The ground bedding, however, was prepared in compliance with the nature of the site the temple was to be erected in.

If a building was to be erected on a plain with soft soil, then soil was replaced. The Egyptian could take out a patent today to protect that invention, since the method of replacing soft soils was widely used by the subsequent generations of people. After a foundation pit or a trench had been dug, the Egyptian took away the soft soil, and filled the pit with dry sand to form a required layer. In reality it was a part of the foundation, since compacted sand standed compression very well.

Should it be that a temple was to be erected on a rock, the required area was levelled for the future building. Unnecessary rock was removed and hollows or 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 in the form of a slope.

To prevent the foundation from possible slide during an earthquake, the rock was levelled to obtain a horizontal surface. The builders had to cut a 240x40 m pit in the rock. The pit bottom was stepped to form steps 0.5 m in height. Then this stepped bottom was covered with dry sand, and only then the foundation blocks were laid on the sand padding. That is, a sand padding was always made between the foundation and the rock. This was the practice of all subsequent ancient builders. The present-day builders do not know it, neither they follow this practice.

The purpose of the sand beddings is twofold. On the one hand, the weight load is uniformly transmitted to the ground, hence equal settlements and no concentration of stresses in the foundation. On the other hand, or rather on the same hand, the bedding performs the functions of a seismic insulation system absorbing earthquake shocks and allowing the structure to slide over the sand relative to the ground moving during an earthquake. Almost beyond all manner of doubt, the Egyptians well knew the importance of preparing a ground bedding for a structure. In any case, as early as at the time of the Middle Kingdom (from the end of the 3rd millennium B.C. to the 17th century B.C.), sand paddings, up to 80 cm thick, were made under the bases of columns. The thickness of the sand padding was dependent on the weight of the structure that standed on it. So, in the city of Ramessum the thickness of the bedding under a heavy pylon was twice that under a conventional wall.

The foundations of Egyptian structures feature great diversity. There are very imperfect designs, in which fairly weak limestone blocks of foundations were placed directly on the ground. There exist fairly perfect foundation designs striking us as well considered. So, the third pylon of the Big Temple of Amon has a foundation laid of large stone blocks 4 m long and up to 1 m wide. These blocks were put in sand edgewise, row after row, with transverse girders placed between them. Such a foundation forms a 38 by 6.3 m core, 6 m in height. Undoubtedly, the edgewise-put blocks added to the strength of the foundation when it worked in bending. We shall speak of it on the pages dedicated to the Greeks.

The foundations under the huge columns named after pharaoh Takhark that are standing in the 1st yard of the Big Temple of Amon are of interesting design. The foundation pit for the column foundations is dug in very dense soil. The foundation itself is composed of three courses of freelaid stones, each up to 30 cm thick, separated by sand beddings 10-20 cm thick with a 1-metre thick cushion of sand made under the whole of the foundation. The entire stratified foundation was enclosed by an adobe brick wall. As a result, the sand is well held within the wall without being forced outward. All foundations with sand beddings work as seismic insulators too.

In general, the Age of the New Kingdom saw essential progress in the evolution of the building skill, creation of strong foundations. Foundations were made deeper up to 5-6 metres, instead of 2-3 metres. Conventional limestone was replaced with sandstone. It is clear that the Egyptians tried to make the foundation more monolithic, assembling it of large tightly laid blocks [10].

The masonry wall was made in three courses with the backup filled between the external facings. Thus, in the burial ensemble of pharaoh Josser which included the Step Pyramid of Joser dated from the time of the Old Kingdom, the three-course wall that surrounded the ensemble was 15 m thick and 10 m high. It consisted of external facing plates of limestone, and the gap between those external facing walls was filled with fragments of stones and bricks. The walls of the temples of the New Kingdom were not so thick as those of the more ancient temples, but similarly they were of a three-course type consisted of three independent walls of which the middle one was load-bearing, while the two external walls were facing. No use was made of huge wall blocks up to 10 tons in weight. The builders used small or average stones, several tons in weight. The wall thickness ranged from 1.2 to 4.0 metres instead of 15-20 metres, as the case was in the Old Kingdom [10].

From the standpoint of earthquake-resistive construction, the above-mentioned structure of walls, both in the Old and New Kingdoms featured an essential disadvantage. All the stone blocks were laid in the wall lengthwise one after another with no blocks placed crosswise to tie the parts of the three-course wall. As a bricklayer could say, there were flat courses and no header courses. The wall parts were not tied together to provide its joint work. The wall parts could collide and collapse. At that time more perfect walls were used by other nations.

As to the earthquake-resistive construction, walls of more perfect structure were used in the Sabaean Kingdom that existed at the end of the 2nd millennium B.C. and the beginning of the 1st millennium B.C. on the territory of modern Yemen. In that kingdom, use was made of the so-called "casemate walls" consisting of an outer and an inner masonry wall braced by transverse masonry partitions, which divide the interstitial space into a series of chambers for fill or storage. The two parallel walls were laid on a durable mortar like cement or on asphalt and tied by transverse bondstones, the inner voides being filled with soil, sand, or rubble [6]. The asphalt mortar imparts certain ductility to the facing parts of the walls, the bondstones provide ties between these wall parts and thus the wall integrity. The soil or sand inside the wall well absorb shaking loads during an earthquake.

Probably, the Egyptian builders were conscious of structural disadvantages of their walls and made use of improvements to make the walls somewhat ductile, monolithic, and capable of absorbing shaking caused by an earthquake. What are these improvements?

First of all note that practically no mortar was used in the Egyptian masonry until the Roman Age. Traces of gypsum have been found in some cases, but it is unknown whether it was used as a mortar, or as a lubricant in laying stone blocks. As it has been said above, the mortar is not of importance with such huge stone blocks as those used in Egypt. The stones are held in place by gravity, and to tie them still better together with a view to making the wall monolithic, use was made of dovetail cramps (Fig.16). They were used

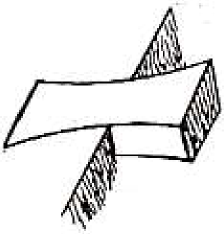

Fig. 16. Stone Tying in "Dovetail" Manner

still during the construction of Pyramids. The relevant recesses were cut in the upper part of two stone blocks to be tied together, and the cramp was fitted into the recesses. All stones of the wall were thus locked to one another. 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 cramps in Egypt were made of wood, granite, copper, or bronze. Archaeologists still now find "dove's tails" made of African ebony. The stone blocks of the palace of Knossos were also tied by wooden cramps.

The temples in Egypt had flat stone roofs supported by columns and girders also 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 Isis in the Delta in which a facing stone block had a tenon on its back side 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.

To end our trip to Egypt, let us have some talk about columns, the most important architectural and structural parts of a building. Still in the 3rd millennium B.C. Egypt saw columns as architectural decoration and roof supports, this tradition being continued in the Middle and New Kingdoms. In the temples, columns were many in number so that they could be compared to a bouquet of flowers. Still more so, as frequently columns were in the form of a lotus flower. In a small temple of Thothmes III, there were about 92 columns situated in an area, 38 by 28 metres in size, at an interval of only 2 metres. There are other examples of this kind..

The Egyptian columns are considered heavy and massive, but this is not always so. The columns of the temple of Takhark (the Ethiopian time) whose coursed foundations were spoken of before, are very well-proportioned, their ratio between the height and diameter of column is equal to seven. At the time of the New Kingdom this ratio was five and four, i.e. the columns were massive and heavy. Their shape and structure vary with time.

The first stone columns were used in the architectural ensemble of the Pyramid of Joser (the 18th century B.C.). Those were built up to 5-6 m high, they had up to 30 layers of small-stone masonry without mortar. It is clear, that such column would collapse when affected by an earthquake, unless the horizontal layers are thoroughly fitted to each other. The column structure must provide loading and squeezing of each stone layer, which is very difficult to obtain even by the present-day techniques. Such columns, however, were erected. Later use was made of monolithic stone columns whose erection continued at the time of the Middle Kingdom. We shall not consider the advantages of monolithic columns. This is an ideal case from the standpoint of structure resistance to earthquake loads. To cut out a whole huge column free from defects of a massive block is a difficult task. More than that, it is not easy to find such a block. Then at the time of the New Kingdom use was again made of built-up columns, but of another structure.

As distinct from the time of Joser, during which the masonry was laid of small stones, 1500 years later, use was made of larger column blocks. Each course then consisted of two half-shafts, from 0.5 to 1.0 m in height, depending upon the size and material weight of each such cylinder ranged from 6 to 10 tons. To provide uniform loading of such columns with due strength and reliability, the horizontal surfaces of the half-cylinders ought to be well fitted to each other. With two surfaces of a joint it was easier than when there were more such surfaces. To provide the local stability of built-up column elements, the 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 connected at the joint with wooden dovetail cramps fitted into special recesses. In the Large Temple of Amen the cramp was 38 cm long with the maximum width of 11 cm [10]. Such a small width of wooden cramps tying large stone shafts suggests an idea that the cramps were nothing more than assembly elements, but the study of later Greek architectural monuments shows that the cramps were weak, but still structural elements. Later on metallic elements were substituted for wooden cramps.

The ancient Egyptian builders used stone, brick and wooden ceiling and floor structures. Brick was used to erect barrel vaults of small bays of 3-4 m over household structures at the time of the New Kingdom. Use was made of gypsum mortar.

Flat stone ceilings were erected above temples. In this event, the columns were connected at the top by girders only several metres in length. Often the girders were made of granite. Girders spanned between two columns were sometimes monolithic. However, more often, the girders were built up of two or three stones connected to each other. In the Large Temple of Amen use was made of odd shape girders which had their joint ends shaped as two rounded beaks of one girder with relevant holes made in the joint end of the other girder. The weight of monolithic girders might run up to 100 tons or more, as the case was in the Temple of Amenhotep III. As it has been said, the column shaft elements were horizontally connected to each other, while there were no vertical ties between them. They were held together by the immense weight of the girders and ceiling structure. That weight performed the function of cement used now to bond stones. These built-up columns have survived already more than three thousand years.

In short, a system formed by columns connected at the top level with longitudinal and transverse girders tied to each other by ductile fasteners and ceiling slabs and divided into sections of limited length was very stable [10]. Because the ties between the structural elements were not rigid, the immense weight was uniformly distributed. Interestingly, the collapse of a column led to failure of a section, rather than of the entire system, while the rest of structure remained in balance being held by the immense weight.

So, we have visited Egypt where we familiarized ourselves in short with the construction of superheavy structures surviving during 3rd-4th millennia. As far as I am concerned, my notion of ancient Egypt is associated with some mysterious unknowable wonders. This is also the case with the earthquake-resistive construction of ancient temples. During their multimillennium life they stood to many earthquakes. With their weight, inconceivable inertia seismic loads ought to arise in them, and for sure the temples were to collapse as they obviously conflicted with one of the major principles of earthquake-resistive construction - the principle of reducing the weight of structure. More than that, the temple load-bearing structures were made of fragile material - stone, while the joint ductility is a contraversal question. I have attempted above to attribute the seismic stability of those superheavy structures to the interaction between the ductile ground and the building, but this is not enough. To explain the phenomenon of the earthquake resistance of the Egypt temples, it must be specially investigated in detail, as it contains something unknown to us. However, it is absolutely clear, that the ancient Egyptian architects had their own outlook on the erection of temples resistant to earthquake effects. I hope our views of this problem are somewhat in common with their outlook.

After the acquaintance with the most ancient improvements made to add to earthquake resistance of structures, we shall move on to Greece about which, one of Chekhov's characters has said: "There is everything in Greece". Let us see, if that is so.

IN A NUTSHELL - GREEKS

Is There Everything in Greece?

It would seem that we may believe the words of the Chekhov's character saying that there is everything in Greece. Indeed, the influence of beliefs, ideas and attitudes of the Ancient Greeks covered, in addition to Greece, i.e. the southern part of Balkan Peninsula, also the cities and colonies of the Hellenic tribes spreaded over the whole of shores of the Mediterranean Sea, and the northern area of the Black Sea coastal region and Asia Minor. In the 5th century B.C., in the course of victorious Greek wars against the Persian 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, king of Macedon defeated the Persians in Egypt, Syria, and Mesopotamia, and extended the conquests eastwards to Bactria and the Punjab with creation of a series of Greek-eastern monarchies. It is clear, that with such wide spreading of their influence, the Greeks not only acquainted other peoples with their culture and construction skills, but also assimilated all useful they learned in the conquered countries. So they did. However, they did not perceive two things in the construction work used by the conquered peoples. In their monumental architecture, the Greeks did not use domes and vaults. Neither they used mortars bonding masonry. All these had been used at that time by peoples of the East.

It is no mere chance that there were no domes and mortars in Ancient Greece. The Greek builders had their own theory of structures, including their own theory of earthquake-resistive construction they followed, utilizing or rejecting certain construction techniques existing at that time. Let us make an attempt to fancy the conception followed by the ancient builders of Greece when they erected the temples with earthquake resistance improvements.

Even brief survey of the structure of Greek temples leads to a conclusion that they used a very simple girder-column system with ductile ties. The load-carrying elements were represented by the walls and columns carrying the girders supporting the floor decking. The ties between the load-carrying elements were accomplished by means of iron dowels and cramps sealed with lead. The girder-column system prevailed in the Greek architecture both during the classical (the 5th century B.C.) and archaic (the 8th-9th centuries B.C.) periods. Examples of this system will be later analysed.

Since the columns and walls of the girder-column structure of Greek temples worked solely in compression, use was not made of domes and vaults whose thrust would cause horizontal loads on them in addition to their vertical compression. More than that, at that time, it was impossible to provide a ductile tie between a dome and the wall supporting it. And finally, to replace the ductile ties with the aid of dowels and cramps sealed with lead between the elements of built-up columns, between a column and a girder, and between stone blocks of walls with a firm tie, using say lime mortar, is impossible. All this will conflict with the girder-column system having ductile ties between the elements that was used by the Greek builders. That is why, Ancient Greece saw neither domes, nor mortars. Though, Greeks were aware of them. Arches laid of wedge-shaped stones were encountered in the Classic period in the burial chambers of burial vaults. As early as in the 5th century B.C. many vaults of fortress gates were semicircular [11].

There is one more supposition why the ancient Greeks did not use domes and arches [12]. To take up

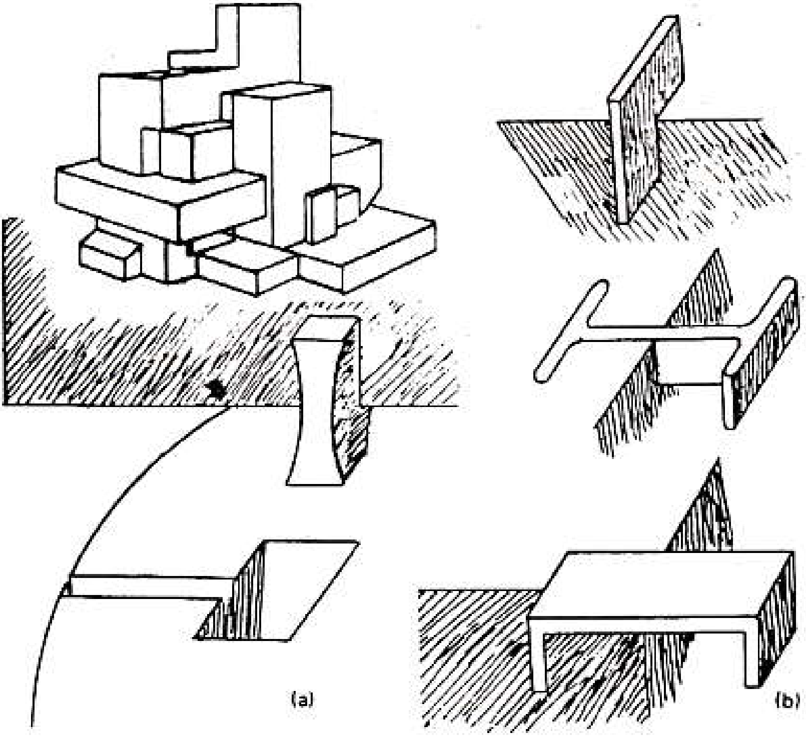

Fig. 17. Methods of Tying Stone Blocks in Greece: (*a*) pins for connecting stones of adjacent courses; (*b*) metallic cramps for connecting stones of a row

the thrust, in case of a dome ceiling, it would be necessary to use additional masses which would add too much to the weight of the structure. The walls and columns that were used could not perform this function. If used, domes would make the Greek structures still heavier and they would be deprived of their distinct architectural composition, and this would conflict with one of the basic principles of resistance to earthquake, i.e. the antiweight principle.

The fact that the builders of Ancient Greece tried to impart enough ductility to the structure of their unique temples is confirmed by the construction of their foundations. Separate foundations erected under the walls and separate columns of the buildings related to the classic and archaic periods. Accordingly, unequal settlements of the foundations did not cause additional stresses either in the flexibly connected floor and ceiling elements, the load-carrying walls and columns, or in the foundations.

One more point of importance is the connection of the elements of Greek temples to each other. The construction of these connections is as follows [13].

To secure stones of one row, use was made of metallic cramps having the shape of simple strips, double-T and U-like, and dovetails (Fig. 17*a*). To fasten together the quadras of two adjacent rows, use was made of pins and the holes for them were 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 had bulges at their ends (Fig. 17*b*). Prior to placing the upper stone, the pins were fitted in place and sealed in by lead. Then the stone was put in place so that the lower end of the pin fitted the hole in the lower stone. It was also sealed in by lead poured through a special hole. The cramps connecting the stones of a row were similarly secured by filling the holes with melted lead. In the temple of Athene Parthenon (to be discussed later) wooden plugs were driven directly into the marble at the centre of the column shafts. To prevent the plugs from swelling, they were made of resinous wood absorbing not much moisture. The plugs were driven in being in the wetted state and dried gradually with time. Fasteners of wood only were used by the Sicilian Greeks in the 6th century B.C. Iron cramps found their applications in the 5th century B.C. There existed combined fasteners, when a metallic dowel was driven into a wooden plug. Note, there were not used fasteners of pure metal, unless they were embedded in lead or wood. It was done not without purpose. The soft spacers of lead or wood cushioned shocks between the hard metal and the hole side in the marble during earthquakes, and there were almost no chipped edges of the holes containing metallic cramps shock-protected with lead or wood, i.e. elastoplastic ties were formed to protect the structural elements from direct impacts.

Therefore, those cramps and pins, lead-sealed in, were important elements used to provide earthquake-resistive protection of Greek temples. Besides, at the same time the lead protected the metallic cramps and pins against rust.

It follows from that was said, that because of the above-mentioned structural improvements a Greek temple may not be considered as an absolutely rigid body. The whole of it consists of separate stone elements having elastoplastic ties between them and a high coefficient of damping due to very accurate fitting of the stone blocks to one another. Even a column composed of separate shaft drums is rather a flexible pillar. Therefore, it may be said that the Greek temple meets almost all the principles of resistance to earthquake effects. It has good foundations, nearly always it features symmetry of mass and rigidity distribution, it is capable of movements and has a high coefficient of damping due to the ductility of the ties between the elements. In spite of this, most of the Greek temples have been ruined by earthquakes [13], though it would seem that such structures as Greek temples free from side thrust, whose stone elements were loaded but little, compared with the stone ultimate strength, in which construction ties were elastoplastic and all structural elements were laid-out symmetrically ought never to collapse. However, the point is that the great weight of the ceiling being a system of stone girders lifted to a great height raised the structure's centre of gravity respectively. Huge masses of material concentrated at a great height caused irresistible inertia seismic forces during earthquakes and they ruined the structures. There were no inconceivable, enormous weights characteristic of the Egyptian temples which accounted for the mysterious seismic stability. The Greek temples simply were heavy, and their great weights often led to fatal results.

Some more talks before proceeding to the anti-earthquake improvements provided in the actual Greek temples. Somebody, maybe many people, may have not agreed with my words that the ancient architects distinguished between a structure not resistant to earthquake effects and an essentially different building well standing earthquakes. In a building of seismic stability everything must be penetrated by the idea of resistance to earthquake effects.

We are encountering this versatile concept of resistance to earthquakes in the Greek temples. What is the reason a construction method is used for? Whether it is for seismic stability, or for some other reasons? An example is as follows. As known, in Ancient Greece there were a few orders. In classical architecture, an order is a particular arrangement of columns with an entablature having standardized details. The Greek orders were the Doric, Ionic and Corinthian. The most popular in Greece were the first two orders. The Doric order stands for the column and entablature developed by the Dorian Greeks, sturdy in proportion, with a simple cushion capital, a frieze of triglyphs and metopes, and mutules in the cornice. In their proportions the columns of that order were compared to the male figure. Later on the Ionic order was developed by the Ionian Greeks. This order of Greek architecture was characterized by columns with scroll-shapes on either side of the capital. The column and entablature originated by the Greeks had a capital with large volutes, a fascinated entablature, continuous frieze, and usually details in the cornice. The columns of this order are more slender and lighter resembling a female figure. The Corinthian order was characterized by acanthus-leaf capitals and ornate decoration. Here is a question for quick thinking persons. What was the purpose of the Ionic order? Whether it was used for architectural aesthetics, or maybe the objective was to satisfy our principles of earthquake-resistive construction by reducing the weight of the structure.

Here is one more example. Looking at the exterior face of a Greek temple surrounded by columns on all sides, one sees all columns equal in diameter, standing vertically at equal spans [13]. 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 others. The span between these columns and the nearest ones is decreased, and, finally, they are inclined inward.

What is it? Whether it is for correction of optical distortion, or it is an antiearthquake resistance improvement. It is clear, that from the standpoint of seismicity, it is 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. Why did ancient Greeks use those improvements?

To my mind, all problems of architecture and construction were tackled by the ancient architects in a comprehensive manner, combining aesthetics, seismic stability, and all other problems we may not even know what they were up to. Now, the time is to deal with actual structures.

Temples...

Let us consider some Greek temples. These are buildings devoted to the worship, or treated as a

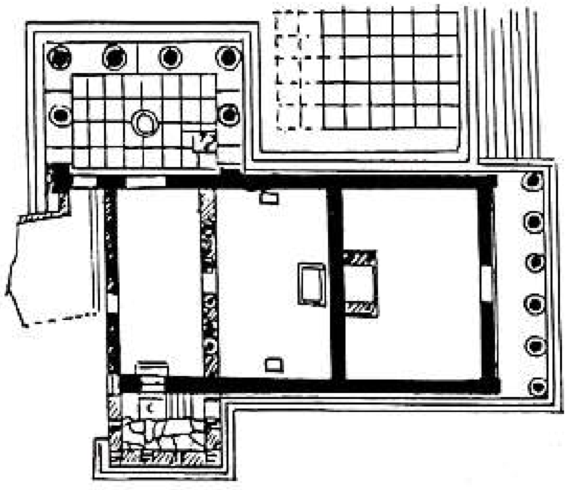

Fig. 18. Asymmetric Plan of Erechtheum

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) the temple is devoted to and inside and outside of which rites are conducted in honour of a given deity. Naturally, the ancient Greeks put a lot of their talant and skill into the erection of these edifices. We shall not follow the hronology in considering some of these temples, rather we shall select what we are interested in, following our logic guideline.

We'll start with Erechtheum, a marble temple built on the Acropolis in Athens with shrines to Athene and Poseidon. Finally that temple was destroyed in 1852. However, it was thoroughly restored at the beginning of our age [14]. This temple differs from all other Greek temples in its complete asymmetry. It consists of a rectangular building (Fig. 18) and three porches tied to it. These have different rigidity and different depth of foundations. The ground under this edifice is heterogeneous and the building is situated near a precipice which makes the wave picture of earthquake effects complicated. Besides, it is partially supported by the ancient temple of Hecatompedon destroyed during the Persian wars. In this case we may speak neither of symmetry, nor equal distribution of rigidity and mass. Why did it happen? I refuse to admit that the ancient builders started the design and construction of Erechtheum as late as in 421 B.C. were not aware of the symmetry requirement 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. Erechtheum 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 of him where his trident struck the ground; the shrine of Olive, the tree sacred to Athene, which she planted, and for which awarded Athens in her contest with Poseidon, and other memorials. All that had to be coupled in an architectural way, and since all the shrines were located at different ritual levels of the rock, the builders had to construct a temple strange in configuration. More than that, there is a hypothesis saying that this temple was not finished, otherwise it would be still more complicated. Therefore, the builders of Erechtheum were compelled by exceptional circumstances to disobey the major principles of earthquake-resistive construction, such as the principles of symmetry and uniform distribution of masses and rigidity. The other structural methods aimed at improving the seismic stability of the temple at that time had been used by them. Those methods are as follows.

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 irregular surface of the site rock. All buildings erected on the rock of Athens, such as the Parthenon, Propyleas, and Erechtheum too are insulated from a direct contact with the rock by means of filled packed soil to provide a uniform ground bedding for the buildings. The stone foundation of Erechtheum is not a solid massive. 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 and there is a risk of landslide under these porches. The main seismic stability improvement of Erechtheum is represented by the masonry dry-laid of stone blocks thoroughly fitted to one another with bonding joints and connected by T-shaped cramps and pins lead-sealed in place (Fig. 19) [13]. To prevent sliding during an earthquake, the 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 a high coefficient of friction to the masonry. The block slabs of the three-step stereobate upon which the walls and columns are erected and of the plinths are laid flat on each other to form the base binding of the temple closed in the outline. The wall base is laid of large blocks up to 1.0 m high, up to 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. 19.

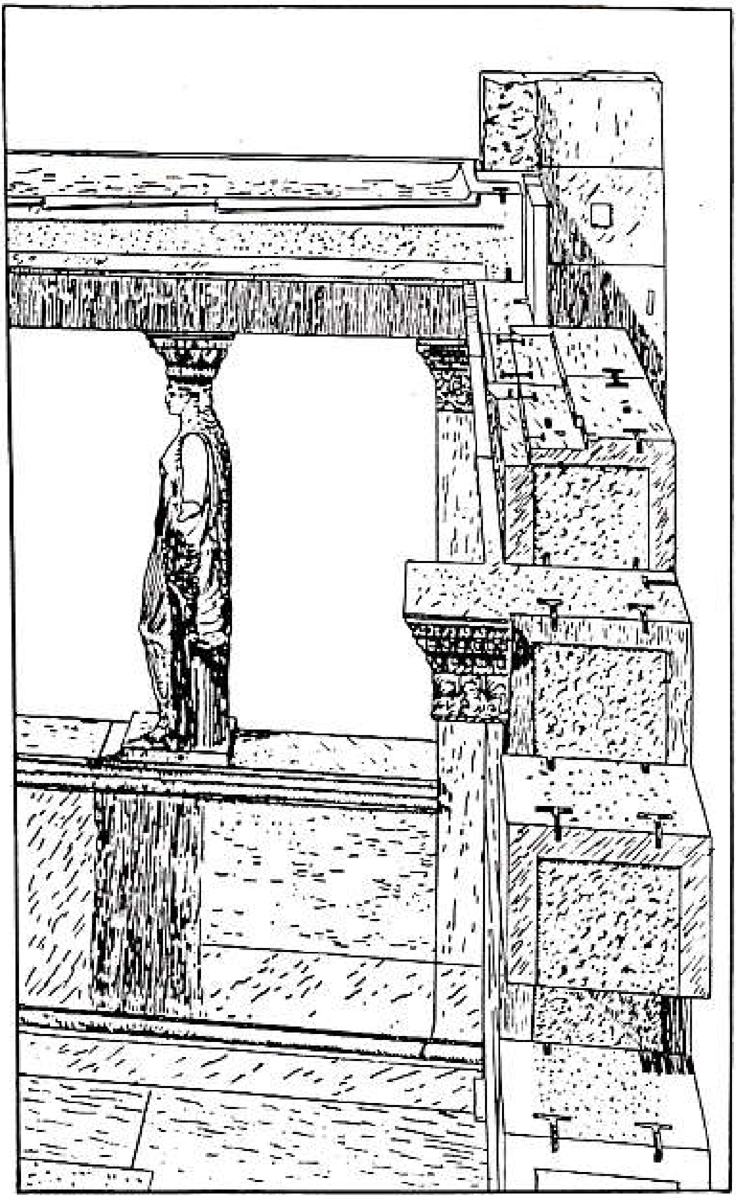

Fig. 19. Use of Metallic Cramps to Provide Special Ties of Erechtheum Stone Blocks

The planning of Erechtheum takes into account the fact that its western part is heavier than the eastern part (Fig. 18), and the porch of caryatides and the northern porch added to the western part on two sides serve as if counterforts to fix this heavy portion of the temple in case of an earthquake. By the way, according to some investigators, the quality of the western wall is lower than that of the other walls of Erechtheum [14].

Erechtheum has been considered herein to show its complete asymmetry. Even the northern porch and southern porch of caryatides added to the main building which in addition to the aesthetic and worship purposes perform the functions of counterforts, have no common axis of symmetry, which naturally caused additional torsional moments in the temple's structure during an earthquake. To my mind, this example will help the modern builder understand that it is no good to erect asymmetric buildings in the highly-seismic regions.

The floor and ceiling structures of Erechtheum are similar to those of the other Greek temples, i.e. the wood-stone type, and we shall not dwell upon it here. To this end, we'll use another example typical of Greek temples.

In the discussion of the Greek temples it stands well to reason to consider the Parthenon - one of the most perfect masterpieces of the world architecture art. This temple of Athene Parthenos (the maiden), was built on the Acropolis at Athens in 447-432 B.C. by Pericles to honour the city's patron goddess and to commemorate the recent Greek victory over the Persians. It was designed by the architects Ictinus and Callicrates with sculptures by Phidias, including a colossal gold and ivory statue of Athene. The face, throat, arms, and feet of the statue were ivory; the clothing and armor were gold, and the complete statue was forty-two feet high. The Acropolis contains the following essential memorial structures: the Parthenon, Erechtheum, and finally the most famous propylea. It is famous for its beauty and originality, completed about 432 B.C. Of all these structures we shall consider only the Parthenon.

A.S. Bashkirov describes the workmanship of this temple as follows: "The workmanship of the 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 for the severe necessity to contribute to the structural stability of the structure... . The equal and neat distribution of masses in the whole of the temple together with slender verticals imparts lightness and highly credible stability to the building" [8]. Some words about prof. A.S. Bashkirov who has much contributed to the history of the earthquake-resistive construction and his works must be acknowledged in this book. His papers were published still before 1917. They were devoted to the archaeology of the northern Black Sea coastal region. To my mind, his principal work is represented by the four-volume work Aseismicity of Ancient Architecture (Antiseysmizm of drevney arkhitektury), 1945-1948, the Proceedings of the pedagogical institutes of Moscow, Kalinin and Yaroslavl. Today his books are bibliographical rarities whose author is known only to a few people, though the books are unique in their contents and interesting in design. More than that, it is known that he has started a similarly fundamental book on the earthquake-resistive construction of the Middle Ages, but what has happened to his manuscripts is unknown. There is a legend that he has predicted a severe earthquake in Central Asią, and it happened unfortunately in 1948, in the city of Ashkhabad. However, let us return to the Greeks of past time.

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

The ground bedding under the foundation of this temple was made in a heavy tightly-compacted fill with the so-called "Persian rubbish" added to it later, i.e. the debris material left after buildings were destroyed by Persians. A giant gravity wall held the fill to form a territory far wider than required for the temple. The foundation of the Great Temple was laid by the builders in this fill. The progress of the construction was slow, and at the time of Pericles the temple was

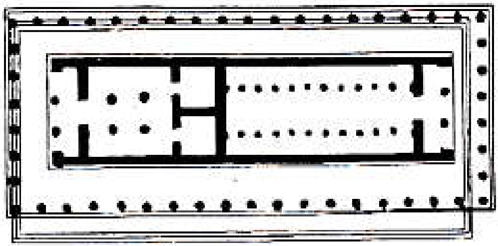

Fig. 20. Parthenon Plan

replanned to start the construction of the Parthenon in proportions quite new. The new builders reduced the length of the Parthenon compared to the old temple, but made it wider. They partially utilized the old foundation that became stronger, by shifting the whole of the building farther from the edge of the rock. The remaining unloaded part of the old foundation at the gravity wall side serves as if a counterfort supporting the base of the new building. The builders did not take a risk of erecting the Parthenon even partially on the rock, since the result would be a nonuniform ground bedding. Neither did they use the narrow rib of the rock run from West to East in parallel with the long side of the temple. Placing the building on this rib would threaten to break the building into parts during an earthquake. So, the position of the Parthenon was determined by these very conditions caused by the state of the ground bedding, and the requirements for the harmony with the landscape and the eminence of the temple.

Figure 20 shows the plan of the Parthenon [11] which is peripter (a temple surrounded by a single row of columns) with 8 by 17 columns and dimensions 31 by 69.5 metres. The outside colonnade surrounds the walls of the cella, the sanctuary of the temple, 21.7 by 59.0 m in size [8]. 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 dimensions are given here to lay emphasis on the proportional ratios between the width, height and length.

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

The existing damage to the Parthenon tells us that the temple has undergone many earthquakes, and it would survive, if it had not been destroyed by an 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 building's centre and scattered the columns of the longitudinal facades. Lying in ruins, the Parthenon allows us to study in detail the small structural improvements used by the ancient Greek builders to protect their buildings against the effects of earthquakes.

The Parthenon is essentially built of marble, bronze in the form of dowels and pins, and lead to seal them up. These materials have the properties that were used to create structures resistant to earthquake effects. 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 show sharp, man-made roughness; second, none of masonry blocks in the foundation, walls, ceiling girders, even the door casing blocks was laid, unless use was made of pins and dowels performing the functions of mortar, but in addition they provide ductile ties between the elements of the structure. The column shaft drums have square holes to receive wooden dowels with couplings [11].

Such a built-up column was far more flexible than a monolithic one which was used earlier. More than that, the built-up column might be in some way a seismic insulator for the heavy ceiling it supported absorbing some ground motion transmitted to the ceiling during an earthquake. The columns, however, could not perform the pure seismic insulation functions, as the girders at the top level connected the columns into a whole with the more firm walls. As a result, the heavy horizontal earthquake loads produced by the heavy ceiling were almost completely conveyed to the more rigid walls of the cella destroying them first of all, and because of their flexibility the built-up columns were affected by these horizontal loads only partially while the firm walls remained intact. Among the ruins of Greek temples one may see fragments consisting of a few columns with massive architraves lying on them, while there are no walls which collapsed. So, the column system has shown seismic stability.

Now some words about the girders working in bending.

Being on guard against failure of stone load-carrying girders laid on the outside columns, the Greek architects of the Parthenon minimized the column-to-column span to 2.47-2.51 m [8]. In addition, to make the girder erection easy and improve the girder strength, the girders were assembled of three plates laid edgewise. In this case, failure of one plate did not lead to the complete failure of entire load-carrying structure. To the point, note that the girders in more ancient temples were assembled of a few plates laid flat which affected the girder's strength. Later, the plates were laid edgewise, as the case was with the Parthenon. The Greeks for sure were able of studying the construction experience and taking it into account.

In some Greek temples clearances were left between the girder plates in order to prevent them from colliding. The walls and massive girders beared the other massive elements of the Doric order and the Parthenon's, roof built of wooden rafters with roof sheathing and heavy marble tiles laid on it. There can be called other earthquake-resistive improvements used in the construction of Greek temples. For example, there existed (also in the Parthenon) double-course inner columns beam-coupled to each other at a level, somewhat above the midpoint of their total height, and this improved their stability. However, all those structural improvements aimed at making Greek structures more resistant to earthquake loads often turned out to be useless because of the unfavourable effects of the great weights concentrated at the ceiling level on the seismic stability of the structures. It was that enormous weight that accounted for the destruction of the Greek temples. Judging from the damage to its individual parts, the Parthenon came through many earthquakes. Only earthquakes could shake it so as to cause multiple

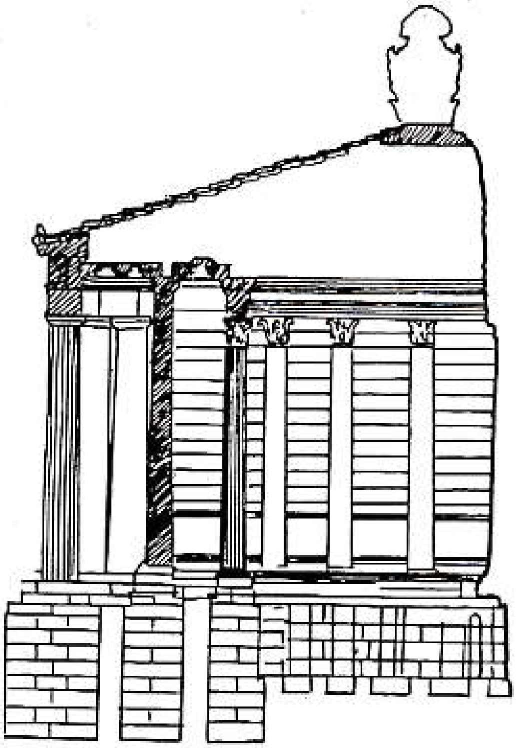

Fig. 21. Separate Foundations of the Tholos Built by Polycletus, 360-330 B.C.

collisions of the stone blocks with resultant chipping along vertical joints of the elements. Cracks in the floor slabs also point to earthquake waves which affected the floor.

Many Greek temples have been destroyed by earthquakes. What the condition of the Parthenon - the ideal realization of the Greek construction art - 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 in the Parthenon. But it is interesting to note that some columns of the Parthenon with the structural elements lying on them are standing in spite of all. Very frequently, columns built up of separate shaft drums are standing among the ruins of other temples. Why is it so? Maybe, certain groups of columns form a flexible structure that does not resonate under earthquake effects, or perhaps a column built up of shaft drums connected by friction and ductile tenons is a seismic insulator. The column is prevented from showing its worth by its connection to the more rigid central structure known as the cella. As soon as this connection is eliminated by destruction, rows of columns thus insulated become resistant to earthquake effects. These facts could be verified, if there would be at least one Greek temple composed merely of columns to provide an equal rigidity of the entire structure beared by the seismoinsulated columns.

In short, from the standpoint of our principles of seismic stabilities, the Greek temples feature two disadvantages: enormous highly located weights and unequal rigidity of the structure.

After we have acquainted ourselves with the standard antiearthquake improvements, let us find cases when the Greeks had to seek for nonstandard solutions to see their ingenuity.

Peripters, rectangular buildings having a peristyle of a single row of columns, were most popular of the Greek temples. At the same time, there existed round peripters and other buildings. According to the writings of Homer, a tholos, a round house, was erected in the yard of Odysseus. The ensemble of the Asclepius shrine on the peninsula of Peloponnese included the tholos built in 360-330 B.C. by Polycletus Junior. This building, whose plan is a circle about 29 metres in diameter, was surrounded on the outside by 26 columns of the Doric order, and had inside 14 columns of the Corinthian order (Fig. 21) [11]. The purpose of this building remains unknown. From the standpoint of seismic stability, the planning of this building is more perfect than that of a rectangular building. Its symmetry may be said to be ideal. The foundations are deep closed rings, separate under the outside columns, the walls and under the inside columns. Found under the central floor are a few concentric walls left from an earlier structure. The foundations of the outside columns and wall have a common top binding. The result is that the building is as if divided into two rings of individual deformations. These are an inner ring composed of the inside colonnade bound by a girder at the top and the foundation at the base, and an outer ring represented by the wall and outside colonnade also bound on the top and at the base. The stone slabs laid on the wall and on the inside and outside colonnades have coffers to essentially reduce their weight. It may be supposed that the roof was also light, wooden, or there was no roof at all. The building has not survived and how it was destroyed I has not found out. But from the standpoint of seismic stability this building practically has no disadvantages.

It is interesting that in constructing their most ancient temples the Greeks were aware of the importance of a strong base under them. The temple of Hera (Heraeum), the 8th century B.C., was built on the same peninsula of Peloponnesus, in Olympia, on grounds of bad nature deposited by a mountain river. The base rock lied deep, and the surface strata were clay quick grounds lying close to the surface of underground water. Besides, those areas suffered from frequent earthquakes [8]. So, the temple of Heraeum was erected on a special man-made platform 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 platform, and the temple walls of mud brick with timber frames were then erected on the 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 had been built of short-lived materials, this temple existed more than a thousand of years, till the 4th century A.C. This was with frequent and careful repairs and replacement of timber columns with stone columns.

There is another case with the temple, the 4th century B.C., built in honour of Athena, on the peninsula of Peloponnesus, in the city of Tegee, the capital of Arkadhia. This temple was destroyed because the builders failed to implement the earthquake-resistive improvements of that time. Its very shallow foundations were laid in weak alluvial soil, and at once for the whole of the temple, without reinforcing the elements under heavy vertical loads. And only some of the stones were interconnected by metallic fasteners. Because of this, the masonry joints broke apart everywhere due to stone blocks sliding during an earthquake. In the destruction the top portion of the building collapsed and produced deep hollows in the stone floor. This is an example of ignoring the earthquake-resistive improvements used by other builders at that time [8]. Many of the ancient people behaved, like we do, ignoring the legacy of the past and taking no experience of today into consideration.

I recall the following. Some 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. There were present many specialists in the earthquake-resistive construction, 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 was standing on dense basic ground, while the other part of it was standing 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 used 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 was also settling nonuniformly, and cracks occurred in it already at the construction time. It would lead merely to failure in the future, especially in such seismic an area. It seems to me that this fact has been 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 improvements are to be used.

Many words can be said about the wonderful buildings of the Greeks that embodied into practice ideas of comprehensively developed personalities. More than 23 centuries have past ever since the erection of the Epidauian theatre constructed under the supervision of Polycletus Junor. Even now its preservation amazes us, though this structure is based on soft ground. It is situated in a bed dug in a hill slope, and the area is highly seismic. The theatre is a fairly flat and elongated structure whose plan somewhat exceeds semicircle. Till now the theatre is free from hollows caused by ground settlements or bulgings from landslides during earthquakes. All this is accounted for by its construction and design well thought out and good workmanship. From the present-day standpoint of supereconomical construction beyond the brink of reason, the construction of this theatre contains more than enough earthquake-resistive improvements. First of all, the auditorium has a common binding at all sides. This is a strong wall along the external circle, while strong propping walls are erected along the side walls of the auditorium. The ground bedding for the whole of the theatre structure is thoroughly prepared. The massive blocks of the masonry are connected by horizontal and vertical cramps and dowels. The well done runoffs and catch basins add to the earthquake resistance of entire theatre structure [8].

I think it is enough said about the ancient Greek structures and their merits, the more so, that this is not the objective of our book. This publishing answers the purpose of showing the structural improvements that were used to make the ancient Greek buildings resistant to earthquake effects. These improvements are as follows.

First of all, an earthquake-resistive improvement is represented by the fact that the ancient Greeks have used in their buildings only the beam-prop designs rejecting any elements producing thrust, such as arches and domes adding weight to the whole of the structure.

Next, most of the 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 in the base and top levels. The base binding is made in the form of a stylobate of large blocks of hard stones connected by metallic fasteners. The columns are supported directly by the stylobate. The top binding is as if double. It is made in the form of cramp-connected beams that span from column to column known as architraves, and the other part of this binding is at the roof level along the cornice.

The next earthquake-resistive improvement is in that the whole of their structure consists of stone blocks accurately fitted to each other and connected by metallic cramps and dowels sealed in place with lead. The contacting surfaces of the blocks are thoroughly finished to provide more friction. The thorough fitting of the blocks improves the strength of the entire masonry, preventing local concentrations of stresses, hence damage, while the increased friction between the blocks reduces the shaking amplitude of the entire building. The functions performed by the metallic fasteners sealed with lead were discussed above.

In addition to all this we must mention thorough compacting of the ground bedding and foundations made in the form of separate foundation elements under the vertical supports.

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

It is high time to visit some Greek settlements therein local building techniques were well combined with the Greek construction traditions. Certainly, we shall pay attention to the Greek towns in the Black Sea costal region some of which are now on the territory of this country.

Black Sea Coastal Region in Ancient Time

Let us leave for East to follow in the tracks of the Greek settlers. It will be of interest to consider several prominent architectural memorials of that time. In this region one can encounter the combination of Greek and

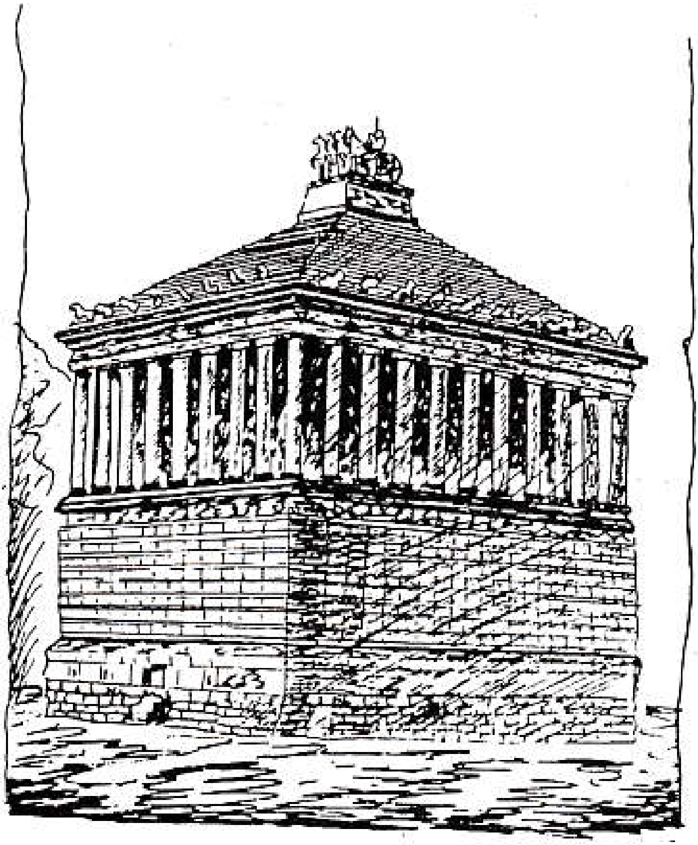

Fig. 22. Combination of Styles in the Halicarnassus Mausoleum, the 4th Century B.C.

oriental forms of architecture which sometimes has resulted in structures prominent from the standpoint of aesthetics and design. To start with, there is an example of poor design as to the earthquake resistance of the structure in question.

In the middle of the fourth century B.C. the large magnificent tomb at Halicarnassus in Caria ordered for himself by Mausolus, king of Caria, was erected by his queen Artemisia with the participation of prominent Greek artists. Probably, satisfying the whims of the

*Fig. 23.*Pyramide-like Platform of Cyrus the Great Tomb

martial and resolute customer, the architects tried to create a remarkable structure and departed from the typical Greek forms and erected the following combined structure (Fig. 22). The socle of the mausoleum was continuation of a foundation laid deeply in soil. The next was a very high stereobate which carried in reality a Greek temple, a peripter with 9 x 11 columns. That highly raised peripter was spanned by a small-step pyramid crowned with a Greek quadriga driven by Mausolus and his wife, Artemisia.

Let the consideration of the mausoleum be started as follows. In its configuration it much resembled the tomb of Cyrus the Great, king of Persia, built in the 6th century B.C. (Fig. 23). Merely for the stability of the tomb, a rectangular (in plan) small burial chamber was placed on a raised platform - a base having six steps. All elements of this burial-vault are laid of large limestone blocks. The pyramid-like base composed of steps decreasing in area with height has made this tomb stable, durable, and resistant to all earthquakes during more than 25 centuries. Checks show that the tomb of Cyrus satisfies all our principles of the earthquake-resistance construction. These are principles of symmetry, low center of gravity, proper dimensions, total height not above 11 metres, except perhaps the reduction of weight.

Note, that this tomb in turn duplicated the architecture of the ancient Iranian sanctuary [6].

Our principles of seismic stability had not been met by the mausoleum at Halicarnassus. First, it is not only because of its fanciful architecture, but mainly due to its dimensions that it is known as one of the Seven Wonders of the World. Second, and this is the main cause, the structure was too heavy with resultant overloading of the socle and deep foundation, while the friable colonnades of the peripter and the walls of the cella were unable to support the highly raised pyramid-like body of the ceiling under earthquake-caused loads and effects. According to archaeological studies, the mausoleum was destroyed by an earthquake [8]. As you see, all is in conformity with our principle in these examples.

Now we shall transfer from Asia Minor to the northern Black Sea coastal region. Let us start with the Bosporian Kingdom with its capital Ponticapey, now Kerch. The history of the kingdoms Olvia, Chersonesus, Bosporus covers almost 1000 years from the 6th century B.C. to the 4th century A.C. From Asia Minor we were led to Ponticapey by an analogy of the stepped ceiling structure of the mausoleum at Halicarnassus with the similar ceilings of the burial vaults of the Bosporian Kingdom. However, the similarity is only superficial, and there is an essential difference between them in that the stepped-pyramid ceiling of the former was situated at a great height, while the entire ceiling structure of the latter is fully arranged in the ground and compressed by a tumulus fill.

Let us consider, by way of an example, two tumuli (burial-mound) vaults: Melek-Chesmen and Regal, the 4th century B.C., that survive. The former is situated in the centre of the city of Kerch, near the bus station, and the latter - in the suburb. I was lucky to visit these tumuli.

In the summer of 1989 I was hired to participate in the expedition under prof. A.A. Nikonov to perform researches in the towns and cities of the Crimea with a view to looking for the traces of ancient earthquakes,

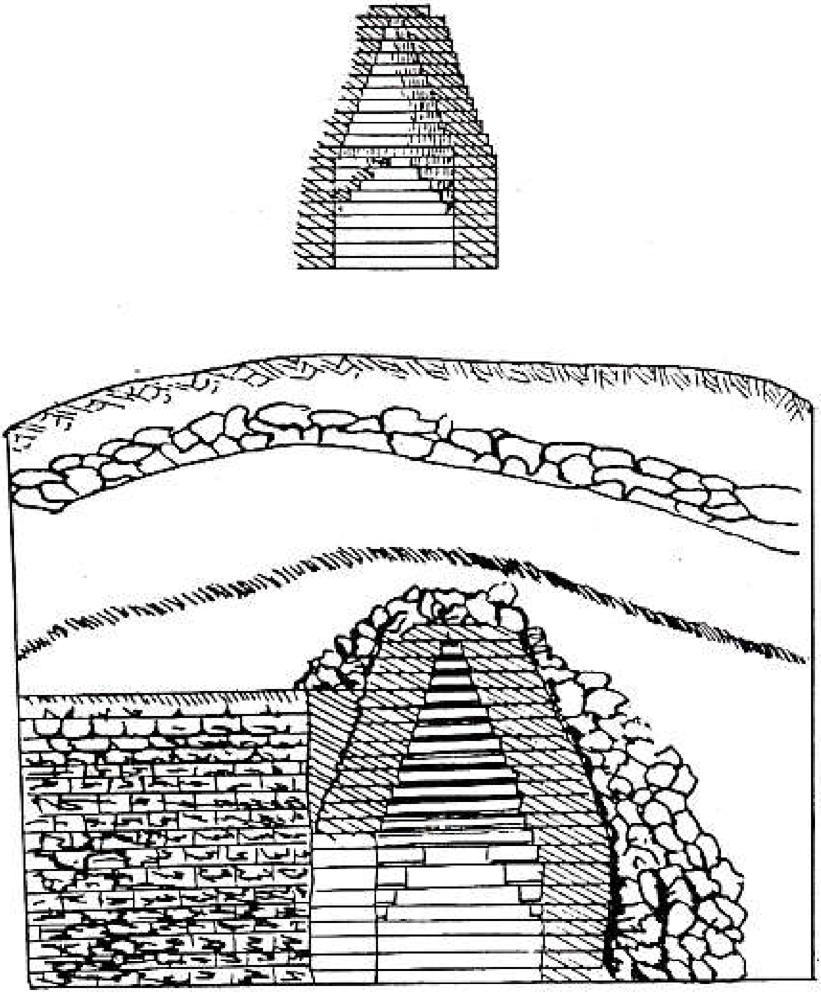

Fig. 24. Multicourse Structure of Regal Tumulus

including those mentioned in the historical documents. Such investigations were required for setting the design seismicity applying to the different regions of the Crimea, mainly for the area of constructing the Crimean atomic power station on the peninsula of Kerch. Traces of severe ancient earthquakes on this peninsula have been found, including those mentioned in the chronicles. At any rate, the tumuli in question have survived several earthquake disasters during their life of more than two millennia. Traces were left by these disasters, but they caused no essential damage to the whole of the structure.

The longitudinal section of the Regal tumulus and the cross-section of the entrance to the tumulus [15] are shown in Fig. 24. Note, this tumulus has been called regal for its huge size and its absolutely unique stone construction. It has no analogue in the world, perhaps there is some analogy between it and the underground domical vaults of Mycenae. The tumulus is composed of a chamber and a long, deep entrance passageway, known as a 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 courses. The blocks are well chiselled on the face side and accurately fitted to each other in dry manner. Next is most interesting. A domical ceiling in a corbel manner starts with course 5. Starting with the corners, massive blocks are projected, each course progressively, thus narrowing the space above the square plan of the chamber to form regular polygons by five courses which develop into a circle with height. Still more 12 courses produce mathematically true circles narrowing progressively with each course to form a conical dome. The last upper circle is covered on the top by a solid massive plate. An interesting and reliable decision has been found in solving the problem of coupling the square part with the round domical ceiling by means of stepped pendentives forming transitions between superincumbent round courses of the dome masonry. The height of the chamber is 9 metres. The rings of the conical dome are assembled of long curved stones.

The conical dome marked by concentric circles extending into the darkness impresses deeply.

Adjacent to the chamber from the southern side is a dromos, the long, deep passageway 36 m long, 2.5 m wide, and up to 7 m high. It is also dry laid of huge limestones accurately fitted to each other and forming a corbeled narrow vault as shown in the figure.. The other details of the tumulus are as follows. The chamber and the dromos at the outside are buried in large natural stones laid in 6-7 courses at the base and 3-4 courses over the dome. This can be seen in Fig. 24. The soil fill of the tumulus is neither simple. The first course hardly covers the chamber dome and dromos together with the stone fill. Next, the whole of the fill is covered by a thick course of sea grass and seaweed. The second course of the tumulus fill, several metres thick, is covered with three courses of quarry-stone to form as if a stone mound. Finally, the third course of soil fill completes the construction of the tumulus. The whole of the fill above the vault exceeds 17 metres, the base outline of the tumulus is 250 metres.

There can be no doubt about that the whole of the multicourse bulk of the tumulus with the kernel in the form of a stone vault must be treated as an integral structure embodying the advanced creative architectural and construction thoughts of that time. Note, that at that time the burial problems and life in the other world were treated as very important, for which reason such worship structures embodied all best and progressive aimed at the importance and durability of those structures. Implemented in the tumulus structure is the idea of providing the vault covered by it ever lasting existence, protecting the vault from elements and external effects.

The seismic stability of the whole structure of the tumulus starts with the vault itself whose construction material was very well worked with the structure designed on a high engineering basis of that time. To prevent almost cyclopean stone blocks from sliding over each other, their contacting surfaces were made rough. In addition to that, the thrust forces in the dome and in the vault ceiling of the dromos tend to push the stone blocks outward, but this is counteracted by the external loads caused by the stone and soil fill smoothly compressing the entire structure from the outside and imparting it stability in case of ground movements. With such a simple structure, the task of coupling the round conical dome with the square chamber has been carried out on a basis of perfect design. The structure impresses one by its reliability and strength. At that pre-Christian time the solution of the problem of coupling a domical ceiling with a square (in plan) building was a matter of distant future. In this case, the problem was solved in advance. Two things in this tumulus have impressed me. First, this is the integrity of architectural task and structural implementation of it. Second, the logic of the grandly conceived plan, accurate calculations of the man who designed it and created an accomplished work of architecture. For the history this tumulus is of the same standards as the Egyptian pyramids and Indian temples.

With the construction of the multicourse tumulus, many things are incomprehensible. If it were built as an air-raid shelter, then it would be clear. The top course is soft, a stone mail under it, next a soft course of ground, elastic damper of grass, again soft ground, again stone mail, and finally a superstrong vault. Why did the ancient builders do so? There were no aircraft, bombs and persons from other planets at that time. Nothing, except for the elements threatened the tumulus from above. Was it so from underground? Certainly, earthquakes were probable in this area and they did take place. But did the ancient builders think of it? Most likely they did. And how and what did they fancy? That is an enigma. What for did they lay the thick course of sea grass? Long ago I heard of this course of grass encountered in the Greek structure near the Black Sea and thought what a nonsense it was; sea grass ought to decay, since it was not like the rush insulation course above the foundations of the memorials found in Central Asia that will be discussed later. Finally, I saw these insulation courses of sea grass by myself. They were used by the Greeks and their followers in the floor and ceiling structures of almost all buildings. These courses of sea grass feature

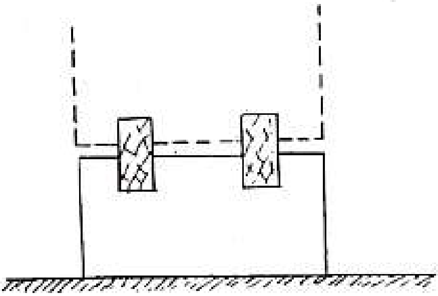

Fig. 25. Seismic Insulation of Temple, Ponticapeya

exceptional durability, far greater than the wood does. Such an elastic course forms a sliding surface. What for was it used? Nobody, including highly skilled archaeologists could explain it to me. Again, what for was there a course of stones in the tumulus? Maybe it is against robbers. In short, whatever the ancient builders did think of and how they did design this tumulus, the result was an earthquake-resistive structure that has survived till now.

The structure of the Melek-Chesmen tumulus is approximately the same, but it is smaller and its dome is stepped rectanglar like that of the Mausoleum at Halicarnassus. Further we'll not discuss structures in the Black Sea coastal region, but to save space of the book, we'll visit only those areas and at the proper time to note the details we are concerned with.

If from the embankment in the city of Kerch you go upstairs by the beautiful stair decorated with chimeras to come up the mountain of Mitridat, and have gone around its top, you will see the excavation of Ponticapeya: 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 whole of perimeter as shown in Fig. 25. No doubt, these grooves were done to fit wooden bars between the wall and the foundation. The purpose of these bars was unambiguously to serve as seismic insulators to damper shocks transmitted from the foundation to the walls in case of an earthquake. At a certain time the city severely suffered from an earthquake which is indicated by the walls of buildings that fell in one direction and by the fault scarp which crosses the entire city.

It has been said many times, and I'll say it once more that much attention was paid to the foundation by ancient builders. In the same city of Ponticapeya, in the course of building its basic structures, the builders encountered complicated ground conditions. They had to erect buildings on hill slopes of stratified sandstone rock easily giving way to settlements and shifts. 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 [15]. The first course is edgewise laid to make these blocks better accept bending moments which occur in them due to unequal settlements or from propagation of earthquake waves. The 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 which certainly reduces 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 of revolution.

Quite recently, the foundations of a large building that might be 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 heavy earthquake took place in this area according to the historical data. I saw the method of lying the huge blocks of foundation. It was well seen in the excavation (Fig. 26). The first underneath is a thick course of clay. Then there are natural stones of middle size. Next, a levelled fill of small stones is on which the foundation blocks are laid. The purpose of such a construction is

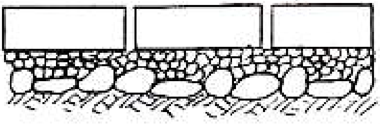

Fig. 26. Seismic Insulation of Foundation Blocks

clear; uniform distribution of load and reduction of earthquake effects.

Note, that no primeval construction techniques that existed in native Greece were used in Greek settlements. The influence of East was telling upon them. For example, lime mortar was used in the above-mentioned foundation. On the contrary, dry-laid stone blocks with use of cramps and dowels sealed with lead to connect them are encountered very seldom. Though, examples are known showing that the classical

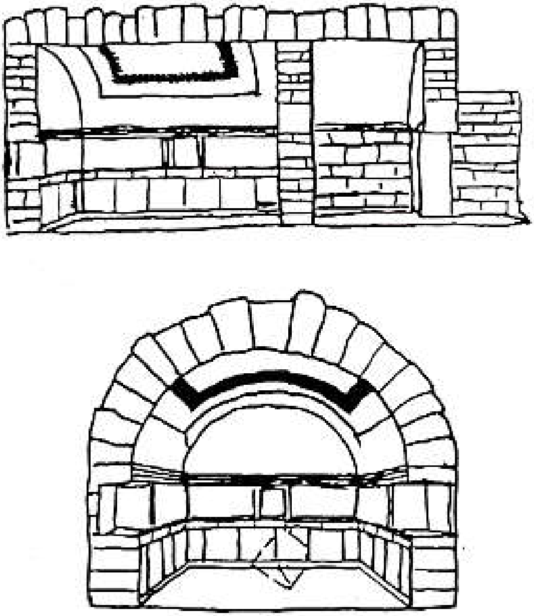

Fig. 27. Burial Vault with Double Ties

construction techniques of 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 situated on the hill of Vasyunkin. The vault was called the Large vault [15]. Nearly all antiearthquake techniques known at that time in West and East were successfully combined in the construction of that burial vault. For the longitudinal and cross sections of this vault, see Fig. 27. It consists of two rooms, an ante-room and a chamber. It is of particular interest that the ceiling is in the form of a barrel vault not used by the Greeks, while the keystones of the vault are connected in the Greek manner by large iron (not a Greek style) cramps sealed with lead. The transverse stone walls serve as the diaphragms for the barrel vault. Laid in the walls are long interconnected stones that are used as the belt of the entire structure to compress it and take up the thrust produced by the vault. This structure is about 4 metres wide and about 5 metres long. As you see, the dimensions of this burial vault are moderate; all is symmetric, maybe its weight is a bit great, but the whole of the structure is situated in the tumulus, and ground fill compresses it around. In the long run, the burial vault survived not less than two millennia standing to all underground storms until it was found by investigators.

All these were examples of successful designs. The structures of poor design most often had not survived. However, the following cases are known. The defensive wall of the Chersonese collapsed in some places several times, probably, because of earthquakes. This is because this wall has bays up to 100 m long that were not supported by counterforts and towers.

Further studying the ancient Black Sea coastal region, one may encounter many interesting structures, but it is high time to proceed to other regions. Two examples more to complete the investigation of the region.

In Olvia situated in the north-east area of the Black Sea coastal region, wide use was made of substructures of ash and clay courses laid as foundations under the walls. Depending upon the lay of the ground, nature of soil and type of the structure, the dimensions of these substructures vary within very wide limits, being from 4.0 m to 12.0 m wide and from 0.25 m to 5.0 m deep [15]. In reality these substructures were a man-made stone material formed as the salts contained in the ash permeated the clay to produce an artificial saline soil - a good base for erection of stone buildings on it. This man-made base was frequently used in case of construction on weak grounds.

The other example is as follows. In the construction of the defence structures in the Chersonese, the stone masonry was frequently reinforced with timber. We have seen the use of timber and wood many times and shall encounter not once at other time and by other peoples. So, in our case, to make the walls flexible and monolithic, and reduce their weight, timbers were laid in the wall masonry after being impregnated with something for sure to prevent decay. Of particular interest in this respect is the tower of Zenon. A timber framework of vertical and horizontal beams was embedded in its masonry.

Now, following the spiral of time, we shall devote ourselves to Rome, since "All roads lead to Rome", though, to my mind, it would be more correct to say that all roads lead to Greece. Much has been given to the world by the Greek culture, from philosophy, poetry, the fine arts, architecture to sport. The influence of the beliefs, ideas and attitudes of the Ancient Greeks is still felt today. During the fourth century B.C. the Greeks began to plan their towns or settlements on a rational basis. In new towns, they were able to take into consideration such things as exposure to sunlight, wind direction, conditions for access and good drainage. The influence of Greek culture got about in the world through their conquests extended to India, deep areas of Central Asia, Egypt. Their architectural monuments affected by earthquakes and bearing traces of their effects must be well studied in order to properly erect present-day earthquake-resistive structures.

ROME AND BYZANTIUM

Everlasting Alliance Between Concrete and Arch

In the 8th century B.C. a group of reed huts beside the River Tiber gradually developed into a town, Rome, which became the centre of a great empire. The history of Rome is conventionally divided into two large periods: republican from the expulsion of Traquin the Proud in 509 B.C. to the origin of Roman Empire in 27 B.C., when Octavian took power as what was effectively a constitutional monarch with the title of Augustus; imperial till the transfer of the empire capital to Greek Byzantium by emperor Constantine at the end of the 4th century A.C. Our task in this chapter is very modest. Without considering any historical origins and development of construction techniques in Rome, we shall make a short report on how these techniques influenced the earthquake resistance of Roman structures and what improvements were made in particular to add to the seismic stability of Roman buildings. Nevertheless, I'll say some 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 Rome state had a large army of soldiers that could be used for public work, and vast numbers of slaves employed as unskilled labour. The great aqueducts could not be built without them, nor would Roman cities have had their excellent water supplies and drainage systems if it had not been for slave labour. Besides, vast riches and resources were accumulated in the hands of the Roman people due to victorious conquests that could be used to pay for any large-scale jobs and expensive construction materials.

This is 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 call for specific mechanisms and skilled labour of stone-masons. This could be ventured only by the Greeks, nearly each of whom was a skilled craftsman or artist. It should be mentioned, however, that in particular cases, the Romans erected structures similar to Greek ones of large stone blocks dry-laid and connected by dowels and cramps. They were aware of how it was done, since their conquests allowed the romans to appropriate both wealth and knowledge. Usually the Romans used quite another method. With the aid of a large army of unskilled workers they prepared huge bulks of fine construction material, stones, bricks, rubble, sand, lime under the supervision of overseers. Next, the structure is built under the guidance of several professionals and an architect. Many monotonously repeated operations are carried out, the facing walls of brick are laid, the gap between them is filled with concrete and stones. Then, a centering of wood is erected and the domes are solidly filled with concrete. As the next step, the erected structure is decorated with facing of beautiful materials and decorative columns. That is the construction technique of the Romans.

Viollet le Duc [12] has used the following figure of speech to show the difference between Greek and Roman buildings. He says 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 wearing a toga which covers and drapes the structural parts of the body.

Speaking about the Roman construction, we have no choice, but to recall Roman architect Vitruvius, late the first century B.C., who wrote a comprehensive treatise on architecture ('Ten Books on Architecture') [16], based on Greek sources and on his own experience. He dealt with all aspects of building, such as selecting mortars, constructing foundations, erecting defence towers, etc. including the health aspects of planning, problems of acoustics, water supply, sundials, water-clocks, and many other mechanical contrivances as well as all the more obvious aspects of architectural design, decoration, and building. His influence was profound, both immediately and in the Renaissance. Unfortunately, he said nothing about erection of earthquake-resistive buildings, and we'll have to look into the problem by ourselves. Much to my regret the work of Vitruvius was not republished in this country for many years. It would be very useful for any builder of today to learn good construction. There are many useful advices in this treatise. The construction technology of that time is also of interest. I shan't be far out in saying that not only we try to construct efficiently and cheaply, the Romans in construction ensured strict saving of materials and financial resources, but they had to build for ever and they did it. Reading the work of Vitruvius, one can get to know lots of interesting hits on determining the quality of building materials, or selecting the ground base for construction, as well as we do by utilizing different instruments. A simple example is as follows. In winter, 1988-1989, I had to examine the effects and outcomes of the Armenian earthquake. I saw the sand that had been used in construction. In many cases, it was sand contaminated with clay or soil forming dusty or tufaceous sand. The other components of the Armenian concrete were defective too. The results are known. The construction elements of such a concrete more than failed, they crumbled to fine pieces and dust. A structure of the strong Roman concrete fell apart into large pieces. Certainly, the Romans might never use contaminated sand for preparing their concrete. They tested the sand very simply. It was poured on a clean white cloth and shaked off. Traces on the white cloth indicated a poor sand unfit for the preparation of concrete. Selection of a ground base for a building is another example. We must carry out ground ringing operations in this case by producing ground oscillations by explosions or impacts of a cast-iron ball with subsequent recording of these oscillations for an analysis. The Romans did the same, but in a simpler way. 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 to erect 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 replacement will be discussed later.

So, the age of Roman building technology is characterized by two new elements: the invention of a new binding material and thus creating a substance, known as the Roman cement, and the use of vault ceilings in the forms of domed and barrel vaults. That turned to be the very condition for employing vast numbers of unskilled labourers and small-size material. It would be incorrect to say that the Roman cement was invented by chance. In reality, still the Etruscans utilized pozzolan sand as a binding material in erecting vaults. The pozzolan is a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Thus, a new age in the building technology was started. It became possible to erect cast structures. And what is more, in compliance with the prestige of the Roman power it was necessary to erect buildings having large-span ceilings, and at that time such ceilings could be created solely with the aid of domes. However, to build such a dome with curved surfaces of, say, rubble blocks was rather complicated work to be performed by skilled craftsmen. It was much easier to cast domes. Thus, 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 portico Emiliev, 174 B.C. That was a grain storehouse in the port of Emporia on the Tiber.

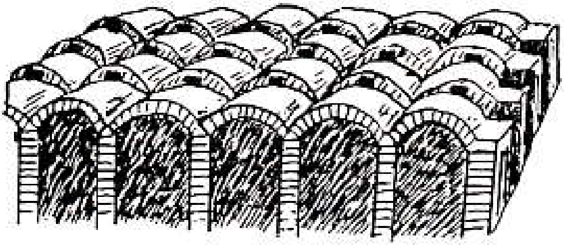

Fig. 28. Portico Emiliev - Picture of Regularity

The dimensions of that storehouse were 487 by 60 metres. It comprised 50 separate sections, each had a barrel vault, 8.3 m in span [11] (Fig. 28). The walls of the building are made of concrete of very good quality and are faced with stone. The ceilings are made of the same material. This portico is of interest because of several points. The fact that this structure had marked the emerging 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 cement. Is this good or bad? Certainly, it is good, though the material is somewhat heavy and that was understood by the Roman builders, and later we'll see how they tried to lighten it. The buildings of that material are strong with uniform properties, and if their structure is symmetric with regular distribution of weights and rigidity, the result is an earthquake-resistive building.

Next, a structure of monolithic concrete will, for sure, possess properties quite different from the properties of the Greek temples made of stone blocks connected by ductile ties. The Roman buildings will be absolutely rigid, and the Greek structure will feature fair ductility. Strange as it may be, but the ancient builders take it into consideration in laying foundations. In the Greek temples the foundations were made independent under the load-bearing elements of a building and unequal settlements of those foundations caused no overstresses in the ductile structure of the building, while in the Roman rigid structure which works as a whole, such foundations cannot be allowed. In the later case, the foundations must also work as a rigid whole. A new foundation has appeared. But let it take its normal course.

Like the present-day builders in highly seismic regions, the Roman builders attached much importance to the selection of ground conditions in construction. According to Vitruvius, an architect at the time of Julius Caesar, bad, weak soils must be removed to the bed rock 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 building, 36 by 100 metres in dimensions. This basilica was built in a site of 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, the builders had to remove the floating earth clay soil by digging to a tuff rock, by-passing and reinforcing the Cloaca Maxima. Thus, eliminating soil defects under the building, they carried out an earthquake-resistive improvement. The weak soils removed were replaced with a man-made substructure represented by a stone platform reinforced with timber poles which served as the base for a huge heavy building comprising arch-spanned abutments. The basilica of Julius bears traces of many earthquakes it has standed to. Its plinth wall shows shifts and projections of huge stone blocks. Many cracks and defects of the building upper part testify to the shaking loads the building underwent during earthquakes [17]. One more interesting example of reinforcing the ground base under a building is as follows.

Beyond all manner of doubt, the cast concrete technology with using facing materials is best represented by the Flavian amphitheater in Rome (69-96 A.D.), the so-called Colosseum. It was capable of holding 50 000 people, with seating in three tiers and standing-room above; an elaborate system of staircases served all parts. The arena, floored with timber and surrounded by a fence, was the scene of gladiatorial combats, fights between men and beasts, and large-scale mock battles. The Flavian amphitheater is interesting in that it withstood many earthquakes frequently seen by Rome which was not the case with many other buildings. However, Colosseum has much suffered from people who made it a quarry.

There is no need of illustrating it with some primitive drawing, all have seen Colosseum in a photograph, in a movie, or maybe someone in nature. The Flavian amphitheatre is a vast oval ring, 156 by 189 metres in area, and 49 metres in height, with an arena in the centre. The whole of the structure stands in a depression having weak alluvial soils. In order to lay a strong man-made base in compliance with the Roman rules, a pit had to be dug with removal of floating earth to a depth of 12-13 metres in an area greater than the amphitheatre itself. The removed soil was substituted for with an entire system of substructures which were to support the huge mass of the building, movable crowds of spectators, and to make the whole of the vast ring stand without failure to earthquakes and work as a whole.

I could not find the data on the underground structure of Colosseum, and it is unknown whether they exist at all. Some information, however, has been attained. First of all, it is known that the substructures had been laid under the whole of Colosseum and that their design had been successful. This is indicated by many traces of earthquake effects withstood by Colosseum, but no load-bearing structures have collapsed. In contrast to Colosseum, imperial forums failed in short time 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 with lime mortar, and most interesting concern of us the "coursed 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" which consists in continuous concreting without ramming. In this case, each 3-4 cm the course of mortar is charged with coarse aggregate. This produces fairly strong homogeneous monolithic medium. This method was used in concreting the dome of the Pantheon that will be considered later. The other method consists in laying "coursed" structures. To this end, as required by the project, 0.10-0.15 m courses of lime-puzzolano mortar are laid either in the walls between the facing stone blocks, or in the foundations. Then, a course of fine aggregate is added to it in about the same thickness. Next, the resultant course is rammed and sprinkled with fine granular material and dust. Due to stone dust, coursed walls or foundations consisting of firm slabs are erected, which being affected by earthquake loads can slide with regard to each other independently, thus reducing the motion transmitted from the earthquake epicentre through the ground. This is one more idea that 2000 years later will be implemented in the form of earthquake-resistive slide belts [17]. The man-made base of Colosseum includes such coursed structures and they probably added to its seismic stability.

The underground parts of Colosseum are not deserving detailed discussion. These are 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 of the structure is an integral strong mass 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-resistive structure with this property ensured by correct configuration, use of vaulted structures of cast concrete, as well as the preparation of the ground base and laying the foundation with seismic-stability improvements under the whole of the building.

Generally speaking, the Romans knew well what foundations must be laid 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 is standing on alluviation soils with a high ground water level to the temple of Vesta in Tivoli which is erected on a rock, we see that they are erected on quite different foundations.

The former is standing on a cube-like deeply laid substructure beared by the bed rock, while the latter is situated in a hollow man-made in the rock and filled with sand [17]. Note that the ancient builders never erected their 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 centuries B.C. the Romans widely used stone in their monumental building, making fairly large blocks of it. First, the masonry was dry-laid, and then stone was used as a facing material with filling the internal space of wall with rubble masonry mortar-bonded. At the end of the 3rd century B.C., the Roman cement appeared, and in the 2nd century B.C. wide use was made of burnt brick. Ever wider applications were found by the construction technology based on the use of small-size materials, bricks and concrete. Columns are laid of shaped bricks with filling the internal voids with concrete. In the period of the Roman Empire the construction of walls and vaults was based on concrete. The brick was substituted for stone as the facing material. The walls composed of brick facing and internal monolithic concrete mass feature an increased strength and rigidity. The cast domes were also of high rigidity. To impart some flexibility to the domes and walls, the Roman builders reinforced the domes with brick ribs. The walls were reinforced by lateral timbers made of burnt trunks of oil-yielding trees. This reinforcing resulted in an equal settlement of the walls and domes. The Roman constructors were professionals of high level. An example illustrating this is as follows.

For a long time I could not understand what provided the uniform settlement and joint work of the brick ribs in a dome and arches embeded in the monolith of the dome and the cast concrete, otherwise additional stresses would occur in the dome and cracks would be formed in that material which was settling in a shorter period of time. But there are no such cracks in the Roman domes built of different materials. This means that the brick and concrete work together. How did the Roman builders get it? All turns out to be simple. It was necessary to count the number of concrete batches in order to provide an equal volume of mortar in the concrete mass and in the joints of the brick arches. The result would be an equal settlement in the domes and absence of stress concentrations. Thus, such a difficult construction problem was solved by providing equal quantities of mortar still 2000 years ago.

As the next step, let us consider in detail such an important element of the Roman structures as domes.

Domes...

All the building structures can be divided into two large groups by the type of ceilings and floors used. The first group includes the buildings in which use is made of the beam-pole system. An example is the Greek temples discussed above. The other group of the structures was presented to us in this chapter. These are the buildings in which the ceilings are made in the form of arches and domes that produce an outward thrust transmitted to the walls and columns. If that is the case, the structures bearing the domical ceiling must be additionally reinforced. Other problems arise. It is natural and easy to couple 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? From the seismic stability standpoint it is of utmost importance. Earlier, we have acquainted ourselves with the good coupling of the dome with the walls in the Regal Tumulus, and we shall see later how it can be done, because it concerns our problem. Generally speaking, the entire history of constructing domes can be represented in terms of the drive for improving their coupling with the walls and reducing their weight.

Their is one more question. Once we are going to acquaint ourselves with the domical systems of roofs, it will be wise to make their general evaluation from the standpoint of seismic stability. One more principle saying: "the simpler the structural scheme of a building, the better its seismic stability" must be added to the seven principles of earthquake-resistive 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 thrust, and thus needs additional inert masses to take up the thrust loads. More than that, on account of the dome height, and sometimes, more exactly because of architectural considerations, the dome is raised on a drum often pierced with openings, which raises the centre of gravity of the entire structure. All this is not good. On the other hand, however, use of domical roofs plays a positive part. The dome itself is a symmetrical structure, and when the building spanned by it is well designed, the structure bearing the dome must be symmetrical. Naturally, it is logical to erect a round building under a round dome, then all weights and rigidity will be uniformly axisymmetrically distributed. This is an ideal case from the standpoint of seismic stability. The architecture of all times and many peoples knew and knows various round structures. Now we call such buildings centrical [18]. These are tombs, temples, combat towers, and many others. Many centrical buildings were erected by the Greeks and Romans. An example of the ideal centrical building may be represented by the two-tier barrel Mausoleum of Helen having a domed vault (Fig. 29), built in 330 A.C., near Rome [18]. The deep niches of the top barrel are spanned by arches which allowed the weight and rigidity to be uniformly shared by the whole of the mausoleum [11]. 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 the ancient craftsmen always attempted to make them lighter and flexible, matching them with some skeleton systems.

In the above-mentioned Mausoleum of Helen, hollow

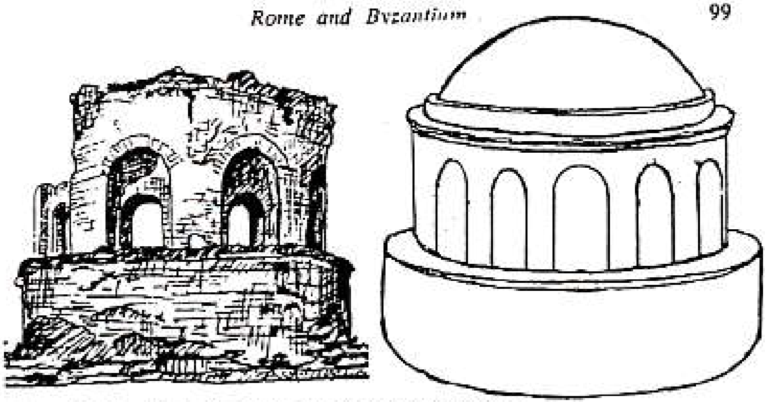

Fig. 29. Centrical Structure of Helen's Mausoleum

ceramic amphores were embedded in the dome to reduce its weight.

It would be unjust to speak of the dome merely as a structure used for roofing buildings to protect them against elements. At all times, in all religions, including fire-worshippers, heathens, Christians, Mussulmans, the dome was always looked on as the incarnation of Heaven [19], the home of God and the saints, and the dome was always associated with miracle, so that the lofty thoughts of religious persons directed to it evoked relevant spirits. Because of this, in constructing domes, the ancient architects paid much attention to them. On one hand, the domes ought to be perfect in construction to withstand any shaking loads; on the other hand, they must evoke elevated feelings. There follow some examples of Roman domes. Let us start with Pantheon, a temple dedicated to all the gods still standing in Rome, an example of unique design and perfect embodiment of the construction technology of that time. Analysing this temple from the standpoint of its seismic stability, we see that Pantheon satisfies all the principles of earthquake-resistive construction that were formulated above. No doubt, Pantheon is a sample, or better to say an ideal of seismic stability, and this is proved by that it has survived almost 2000 years and stood to many underground storms. Its walls show minute cracks not dangerous to its total integrity. Let it be considered in a regular way.

Pantheon was erected in 118-128 A.C. during the reign of Hadrian. It is a simple round temple, which 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 [11, 17]. The thickness of the dome envelope varies from 1.80 m at the base to 1.20 m at the top; in the centre of the dome roof is a space open to the sky.

The barrel of the Pantheon walls is borne on 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 either ancient or present-day authors. Neither I can check it, but there is no doubt that the foundation is of a coursed type, like that of Colosseum, providing seismic insulation with sliding of one course over another due to a sand layer.

It is seen from the above said, that from the standpoint of seismic stability the general configuration of Pantheon is all-right. It is a truly centrical building, all rigidity and weights of which are axisymmetrically distributed in the structure. Now we consider particular structural elements of Pantheon without going into details.

The walls of Pantheon are faced with small brick with large brick slabs laid at 1.0 m intervals which reliably tie 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 sq. metre of domed roofing weighs 7.3 tons, the walls were rather thick, 6.7 m, as has been said above. However, to lighten the walls with a view to saving the materials and reducing their weight without affecting their strength and stability, there were made eight main niches, 8.9 m wide and 4.5 m deep, in the walls (Fig. 30). There are also smaller niches in the walls. All this reduces the weight of the walls by one third. Therefore, the base part of the walls of Pantheon forms eight interconnected masonry piers. The piers themselves have hollows for reducing their weight. The upper part of the wall is more complicated in construction. Here the wall barrel is joined to the dome in which the builders were successful to unite the masses of both through a smoothly cast joint. Strong

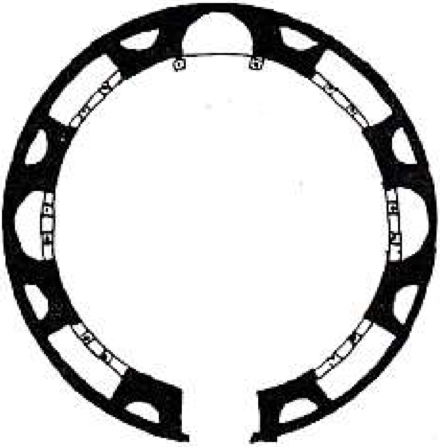

Fig. 30. Voids and Cavities of Pantheon Walls

semicircular brick arches of double curvature running through the entire thickness of the wall are laid in the body of the upper part of the wall. These arches overlap the niches of the lower part of the wall and work like elastic wavy springs which bear the dome with its double skeleton also made of brick.

The cast dome of Pantheon has a very interesting structure. To provide certain elasticity, uniformity of

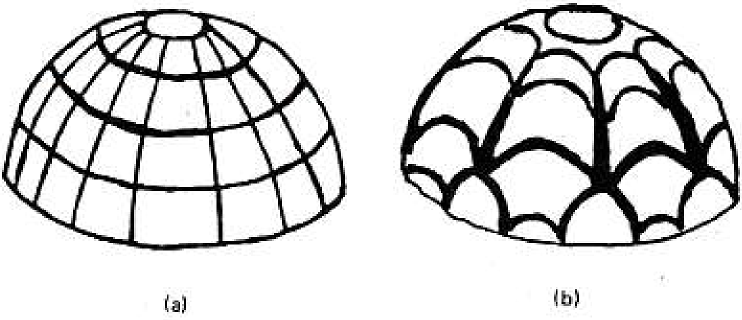

Fig. 31. Brick Skeletons of Pantheon Dome: (*a*) internal; (*b*) external

strength properties, and equal settlements in laying concrete, two skeleton tied systems of brick were embedded in the concrete body of the spherical dome. Note, it is written here "tied system", though there are investigators who assert the opposite. But I do not believe it. I respect the engineering thoughts of the Roman builders and know how they tried to provide ties between their brick skeletons and the body of concrete, and they could not leave untied two skeleton systems in a concrete body. The internal skeleton system of the dome is shown in Fig. 31(*a*). It consists of 5 lateral ribs and 28 meridional ribs. Of course, the whole of the system is closed to form a conventional skeleton. The other skeleton system appears in Fig. 31(*b*). It is situated in the body of the dome monolith, above the former system. This system consists of eight stronger meridional ribs by the number of the wall piers and arches connecting these ribs into a unit skeleton. These ribs of the latter skeleton rest on the elastic arches spanning the wall piers, rather than on the rigid piers. Because of the arches present in the latter skeleton, it is probably more elastic than the former skeleton composed only of straight elements. Being embedded in the softer somewhat plastic homogeneous body of the concrete dome, these two skeleton systems have created a unique dome resistant to earthquake effects. Many diverse domes reinforced by ribbed skeletons were created during the 2000 years that followed, but I did not encounter double skeleton systems in the structures described.

Owing to the builders of genius, the glorious dome of Pantheon has survived and it is impossible to study its structure completely. Usually, only collapsed structures are well studied. There is something misterious in this dome that is difficult to understand from the standpoint of the present-day concepts of the structure work. For example, a modern designer would align the meridional ribs of both skeleton systems without failure to make their tying easy. The ancient engineer constructed them so that they could not match, using 8 and 28 ribs, and 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 the ribs makes the dome more elastic or help it to show its plasticity. All this needs to be studied. To my mind, nobody has seriously studied the construction of Pantheon from the standpoint of its resistance to earthquake effects, though it is a ready answer to the question how earthquake resistant buildings are to be erected. It has been said above, that the Roman builders did their best to essentially reduce the weight of the walls of Pantheon. So they did to lighten the dome. Of course, this was done for the reasons of economy and aesthetics, and, certainly, to improve the seismic stability of the building. The following two improvements were used to reduce the weight of the dome. First, caissons were made along the entire bottom surface of the dome. The caissons were depressions between the ribs of the lower rectangular skeleton. These caissons are emptiness of fairly large size. They are 0.8 m deep at the dome base with 4.0 m in width, and 0.6 m deep and 2.5 m wide at the top. There are 140 such cells in all in the dome. This reduced the dome weight essentially. In addition, the caissons were cast concurrently with the dome. The result is that the spherical envelope rests 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 are greatest. Lighter filling materials of taff and pumice were used 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 brick, materials which badly work in tension.

As you see, shortly describing even one remarkable Roman building makes it possible to understand how sensibly the ancient builders constructed their temples so as to make them stand for ever.

Note, that in 1965 [11] doubt was expressed about the existence of brick skeletons run through the entire height of the dome of Pantheon. It was supposed that the skeleton is run only through the height of two caissons. However, the Moscow International Congress on Shells, 1985, considered the skeleton system of the entire dome. Who is right can be checked–only in the site. To my mind the advocates of the full skeletons are right. It is unlikely that the Roman builders could leave a large bulk of concrete not reinforced with brick, due to, say, the necessity of obtaining uniform settling. More than that, there ought to be something to mount and secure the scaffolds and centering in the course of concreting the upper part of the dome.

The author of Pantheon was Apollodorus 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, and to see the evolution of construction thought, let us consider another dome of about the same dimensions and erected at the same place, but 14 centuries later. In the course of its 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 arising in the course of erecting the St. Peter's Basilica, the Roman Catholic basilica in the Vatican City, Rome, the largest church in Christendom. The present 16th century building replaced a much older basilican structure, erected by Constantine on the supposed site of St. Peter's crucification. A succession of the above-mentioned architects in turn made drastic changes in the design; the dome closely follows a design of Michelangelo. The building was consecrated in 1626.

The basilica is a girder-piller system structure consisting of a few, usually three, naves - middle and side aisles - separated by rows of columns. In erecting the new temple, a more intricate task was set. In addition to the large horizontal internal space, a clerestory ought to be added which could be done by using some underdome space. In this case, however, the dome had to rest on four pillars, rather than on the massive walls as the case was 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. In this event, the dome and the walls could not be a monolithic unit, as the case was with Pantheon. Again, the building centre of gravity was raised on the account of the highly raised dome. All this affects the seismic stability of the building, as it disagrees with the principles of the earthquake-resistive construction. To my mind, this was understood by the outstanding architects who erected the cathedral. The further events took place as follows.

On instructions from Pope Julius II, Bramante Donato di Angelo (1444-1514) designed the new St. Peter's Cathedral (begun in 1506). The total area of the building in that case would be 134 by 134 metres. According to the data available, the dome planned by Bramante was a copy of that of Pantheon with exactly the same internal diameter of 42.3 metres. There is no point in exact copying under changed conditions. Like the case was with Pantheon, the new semispherical dome was supposed to be concealed under seven steps of monolithic concrete with making caissons (Fig. 32*a*) on the inside. It is clear, that such a monolithic dome would be very heavy. In Pantheon it was embedded in the concrete of the wall, while in the cathedral of Bramante it is raised by 48 columns laid out along the perimeter of the dome in three rows. A dome secured in this way could not stand well even to wind loads, not to mention earthquake loads. There were other design mistakes in the Bramante's project of the cathedral. For example, the dome bearing pillars the erection of which was started at his time were weak and the 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. 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 in 1520 the chief architect of the cathedral in place of Raphael. Here our attention must be drawn to the creative activities of Peruzzi who developed centrical plans generally and the cathedral of St. Peter in particular. He sought a new design of the dome. Perhaps, being aware of the disadvantages of the dome bearing pillars of Bramante, he sensibly suggested eight pillars in place of four, reinforcing them with 16 attached columns. As to the dome size, the prepositions of Peruzzi were fantastic. He proposed to erect a dome 66.0 m in diameter in place of the dome 42.5 m in diameter. Next, he suggested to construct an enormous centrical structure with a dome 185.0 m in diameter. That is really too much for a structure of stone, brick and concrete, the more so in a highly seismic region.

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 being improved. The impression is that the architects were interested in the dome seismic stability, rather than in beauties of the dome architecture.

In designing his first project of the dome Sangallo tried to save only the external shape of the Bramante's spherical dome, and in doing so 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 the case was with the structure of Bramante to 7.5 m. The 48 circular columns were left, but in the new project they were attached to a wall pierced by small window openings. All this provided good coupling between the dome and the bearing drum. The suggestions to change the dome itself are interesting and far going. With the external spherical surface of the dome left unchanged, the internal surface has the elevated shape that was used in Europe 100 years ago by Brunelleschi in the dome of the cathedral in the city of Florence (Fig. 32*b*). The curve of Sangallo is arrow-shaped. It is described from two centres which provide smooth conjugation between the dome and the barrel. Further, we'll see the classical use of arrow-shaped domes and arches in Central Asia and know that the arrow-shaped design adds to seismic stability of buildings.

Evidently, the improvements made in the dome of Bramante did not satisfy Sangallo whose attention was drawn by the idea of the arrow-shaped structures and he began to bring it to perfection. The number of intermediate versions of the dome is unknown, but we know the last version. The last project of St. Peter's Cathedral was worked out in 1533. It is preserved till our days in the form of a good model. In this project he probably synthesized the ideas of all previous versions and obtained the following result (Fig. 32*c*). In the last version use was made of two interesting points. The shape of the dome differed from all previous projects. It is ellipsoidal, elongated upward. This at once reduces the thrust caused by the dome and provides smooth conjugation between the dome and the drum. The other specific feature of the dome of Sangallo that imparted it increased stability is that its bottom part is embraced in a belt-like manner by two tiers of arcades. The arcades rest on the thickened wall of the drum which now reliably takes up the thrust caused by the dome. The underdome pillars were reinforced providing quite sufficient strength of the new version. However, the excessively sharpened dome burdened by two tiers of arches had 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. Michelangelo subjected all done before to critique and started the redesign work, having used the experience already gained.

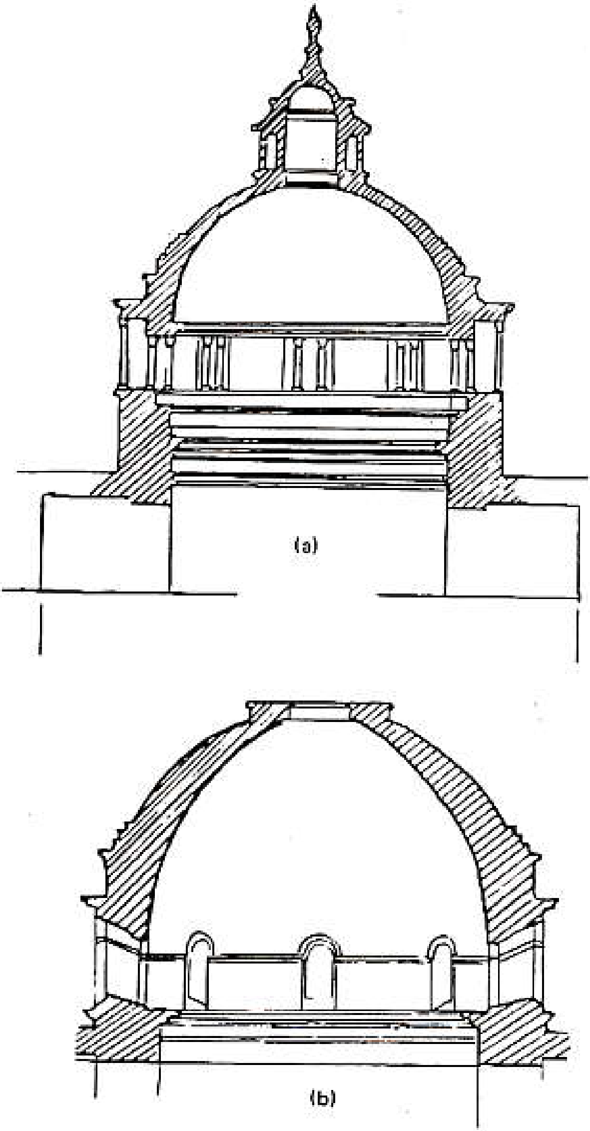

Fig. 32. Versions of St. Peter's Cathedral Dome: (a) Bramante; (b) initial version of Sangallo;

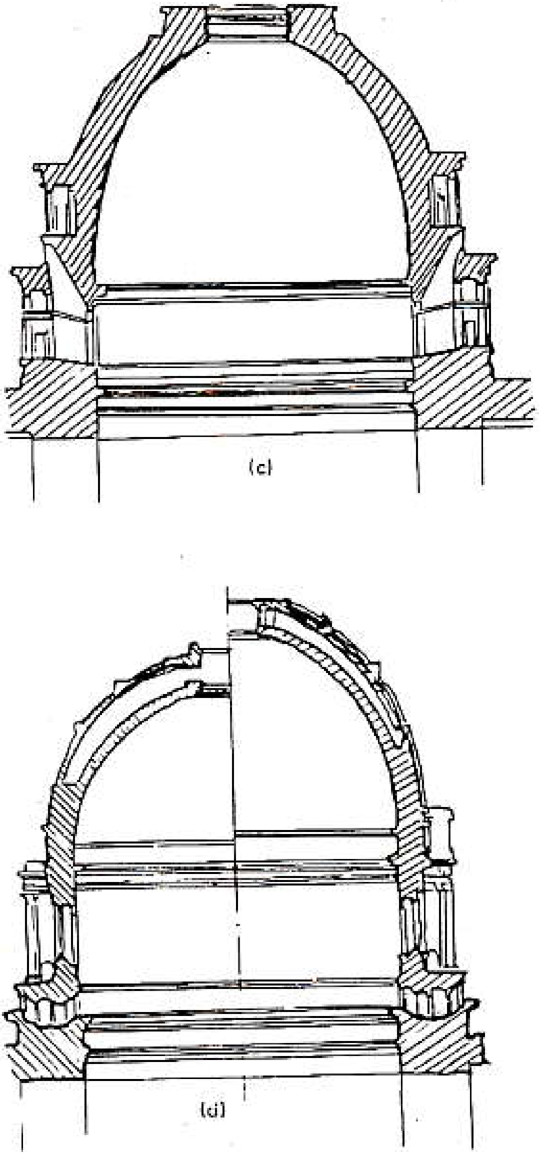

Fig. 32. Versions of St.Peter's Cathedral Dome: (c) final version of Sangallo; (d) Michelangelo Buonarroti

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 cathedral were aimed, on the one hand, at imparting the building monumentality and architectural wholeness, and at improving its seismic stability, on the other hand. Naming the alterations carried out by Michelangelo, we may note that with a view to imrpoving 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, free from sharp turns, walls.

Particular attention was paid by Michelangelo certainly 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. 32*d*) consisting of two shells connected by rigidity ribs. The material in such a double dome is distributed much better than in a solid dome, being most concentrated in the extreme most stressed zones, and the resultant dome becomes lighter. Note, that though the above-mentioned cathedral in the city of Florence had two shells, but only one of them was load-carrying, while the other shell performed the protective functions. In the case in question Michelangelo has made both shells load-carrying.

Michelangelo had time to erect the dome drum. The dome was completed in 1588-1590 by Jackomo del la Porta following the ideas of Michelangelo. He raised the dome by more than 4.0 metres, thus reducing the thrust.

The structures created according to the ideas of Michelangelo feature elegance and delicacy which was not always useful for the building from the durability point of view. The wall of the drum erected by Michelangelo is merely 3.0 m thick. Sixteen counterforts are attached to the wall with placing three circular iron collars into the base of the dome. However, all this turned to be insufficient to stand to the thrust of an enormous dome more than 40 metres 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 [18]. As far as the strength is concerned, the massive drum of Singallo possessed certain advantages. It turned out that combining the principles of structural mechanics and architectural requirements is difficult in such enormous a building as St. Peter's Cathedral. As to whether the principles of seismic stability are met by the cathedral building itself, they are. I do not know on what grounds and how the foundations have been laid, but the structure having the two-axis symmetry satisfies the skeleton principle by which is meant that all load-bearing elements of the building, such as walls, pillars, columns, are interconnected to form unit closed contours to guard against overloads of some elements during an earthquake. The seismic stability of the building was proved by the fact that the cathedral has been standing for more than 400 years.

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 there is in common in the human mentality, though as dictated by the local traditions and construction materials, the structural realization may be different, the ideas being similar. There are some more short dome stories.

The Roman builders paid much attention to lightening different structures, domes in particular. It was mentioned above that clay amphoras and pumice were embedded in the body of the dome of Pantheon. Sometimes embedded in the body of a dome were rings of clay hollow vessels inserted into each other. The rings followed each other [18]. 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 quite another. Our random historic "excavation" is aimed at searching for antiearthquake improvements of the ancient builders in

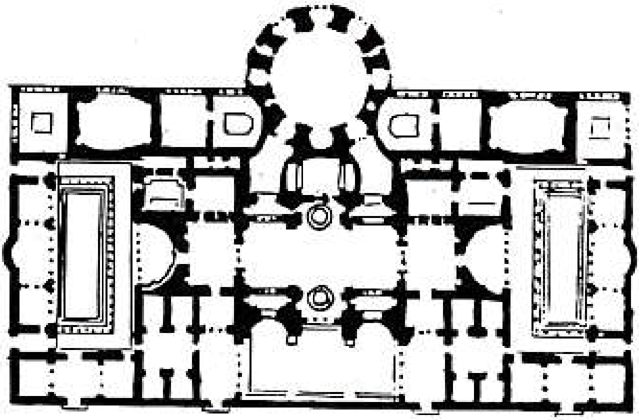

Fig. 33. Symmetric Irregularity of Therm of Caracalla

order to make use of the experience of ancient craftsmen today. Therefore, we'll not continue our analysis of a large number of mausoleums, aqueducts, bridges, villas, basilicas. It seems to me that all said is enough to show the high professional skill of the Roman builders, good organization of the jobs carried out by them, and high workmanship of their structures. All this may be used as a good example to be followed by the present-day builders.

Before parting with the Roman age, let us consider, by way of conclusion, one more kind of structures, therms, which played an important part in the public life.

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. 33) and consisted of symmetrically laid out rooms of different height and area spanned by different structural elements [11]. In short, this building, though having one plane of symmetry, was a very nonuniform and irregular structure. Generally speaking, this does not satisfy the principles of earthquake-resistive construction which reject such construction techniques. To see the results of that violation, we have to consider the structure of the therms in detail.

Referring to the plan of therms, the whole of the structure was concentrated around and adjacent to the round hall with pools that 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 rested on eight poles with attached columns [2]. These were the two highest parts of the therms. These were surrounded by many lower vaulted rooms which took up the thrust caused by the above laid parts. Note, that by the transmitted and accepted thrust forces the building parts were tied to one another, and supported one another. Therefore, there were no antiearthquake joints that would divide that enormous building into separate parts which could independently deform during an earthquake. That was one more violation of the principles of earthquake-resistive construction. From the standpoint of seismic stability, the other disadvantages of that structure may include the fact that it was erected on a hill slope, and, therefore, had a nonuniform ground bedding. All the other elements, speaking of the material of the structure and the strength of the load-carrying elements, met the seismic stability requirements. According to A.S. Bashkirov [17] there is a curious, fairly debatable reasoning on the seismic stability of the structures employed by the therms of Caracalla. According to him, the variety of structures helped the ancient builder to substitute disharmonic chaotic motions for harmonic motions, thus damping the building shaking caused by an earthquake. Saying so, 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 superimposing may occur, for which reason, it is better to use uniform structures in highly seismic areas, in which case stresses will be uniformly shared, otherwise underloads and overloads will take place concurrently. And, the therms of Caracalla can be seen today in the ruined state mainly due to earthquake shocks and then because of shady deeds of people.

This completes our brief survey of Roman buildings from the standpoint of their resistance to earthquake effects. I believe that the analysis made will be helpful to the present-day architects and constructors.

Next, our survey will be continued in the wake of Roman emperor Constantine.

Ancient Craftsmen of Brickwork

In 311 A.C., the Roman empire was in a state of confusion, with four rulers all claiming the title of emperor. By 323 Constantine had emerged as a victor. But, after the years of unrest in Rome, he decided to move the capital of the empire to a safer place. In 330 he chose Byzantium, an ancient and relatively unimportant Greek city, but with a good trading position in the eastern Mediterranean. He intended to call his new capital 'Second Rome', but the name 'Constantinople' (City of Constantine) was more popular. Today the city is called Istanbul.

The Byzantine empire, with its capital at Constantinople, was the Roman empire of the East. It kept alive Roman culture and traditions long after Rome had fallen into the hands of barbarian invaders and its empire destroyed.

The Byzantine empire is probably best-known today for its marvellous artistic tradition. This showed the influence of Greek and Roman styles, but also developed a distinct character of its own, particularly in religious art and architecture which, in turn, influenced every nation that came into contact with it.

Though distinctive enough, the Byzantine construction technology including many elements of new was not as high in quality as the Roman high-standard, well organized construction technology. Hence, failures of Byzantine structures during earthquakes were more frequent than those of Roman buildings. In Byzantine domes collapsed more often. This was the case even with Hagia Sophia (Sacred Wisdom), the great cathedral of orthodox church at Istanbul, which also saw dome collapses during earthquakes [18]. Well, let's follow some order.

Crisis of the slave-owning mode of economy in the

West of the Roman empire brought about a new empire in the East - the Byzantine empire with rudiments of feudal social relations. The same crisis had withdrawn tampted concrete from the arsenal of construction technology which did not find applications in the new social-economic structure. In addition, the puzzolana deposits were now on the territory of Ostgoths, unavailable for the Byzantine constructors. It is curious that the walls of Constantinople erected soon after its foundation (330) following the Roman techniques of cast concrete at the time of the Emperor Justinian (527-565) evoked only astonishment as a miracle. The technique of cast concrete was forgot so strongly that the citizens were astonished thinking that the walls had been chiselled of solid stone, although somewhat similar to cast concrete, cobblestone masonry, was used. The cobblestone masonry was done with lime mortar by coursed laying of crushed stone and mortar in the formwork without tamping. The cobblestone masonry saved much manual labour as compared with the cast concrete. However, the strength of such masonry was much less which, naturally, limited the height of the building in which use was made of the cobblestone masonry [20].

Of the construction materials employed by ancient Rome, the Byzantine empire inheritted stone and brick. First, for construction of new buildings, these materials were taken from old Roman structures. Then, the production of brick was organized in Byzantium. The Roman brick had been made of pure well mixed clay with intensive and uniform burning which allowed production of bricks, 70 by 70 by 8 cm in size, while the Byzantine brick was made of clay not so well mixed with impurities of stone in size 35 by 35 by 5 cm which naturally affected its quality.

In studying the seismic stability of the Byzantine buildings we shall follow the pattern we have used before. We shall not examine the construction methods of that time, nor analyse in detail the history of architecture, but we shall separate that which is new in the structure of Byzantine buildings affecting their resistance to earthquake shocks, analyse then that new using a building preferably surviving as an example, and consider some particular seismic stability elements of the structures built at that time.

It was said above that there might exist two construction systems, the girder-pillar and dome systems, the latter being generally centrical. So, the third system synthesized of the first two has found its use in Byzantium. This was a product of the Christian Age in which large buildings crowned with large 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 piers erected for the purpose or the walls. Such structures appeared approximately in the 5th century. They harmoniously combined the longitudinal and centrical systems and traditions of West and East [21]. Note, the origination of Christianity was marked by an earthquake. According to the Bible, the Resurrection of Christ started with an earthquake which threw aside the stone slab covering the entrance to the cave in which Christ had been buried. Only then the Angel descended and the women came up. Christianity has imposed new requirements on the construction of monumental religious structures. Earlier Temple was accessible only to the chosen persons, the priests, and all religious actions took place outdoors. Now the praying people gathered indoors and there ought to be enough floor area for all of them. At the same time, the entire interior of the temple ought to properly impress praying persons. Hagia Sophia is a good example of the new tasks in architecture and relevant new structural solutions.

Studying the construction art of the Byzantine empire, we cannot but pay our attention to the finest church Hagia Sophia in Constantinople (532-537) started by the Emperor Justinian in 537. The church, with its great domes symbolizing heaven, towered over all the other buildings in the city. The vaulted interior, over 30 metres across and 60 metres high, was the largest of any church in Europe. The architectural form of this church is fairly simple (Fig. 34). It consists of three architectural figures gradually developing into one another: the ground plan rectangle, intermediate oval of the semidomes, and circumference of the dome. All

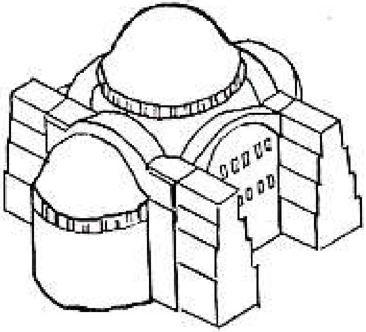

Fig. 34. Nonuniform Rigidity of Hagia Sophia

together form somewhat average between a basilica and a centrical building. The cathedral is vaulted by a large light dome 33 metres in diameter.The dome is borne in an original manner. At two sides it rests on arches built of brick taken from old Roman buildings. Adjoined to the arches are the side semidomes taking up the longitudinal thrust produced by the main dome. At the other two sides the dome rests on the walls reinforced by arches and supported against the dome thrust by pillars - counterforts [18].

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 are laid of hard limestone blocks. To provide uniform load distribution in the stone masonry, plates of lead are placed in the joints between the stone blocks.

That the lead plates having high plasticity and thus protecting the stone masonry against concentration of stresses serve at the same time as insulators of oscillations propagating in this masonry. The Byzantine architects widely used lead in their structures. For example, lead plates were placed on columns and under columns to provide uniform loading of the column and protect it against eccentric compression even in case of unequal settlements of the entire structure. To prevent the lead from being squeezed out it was held by metallic hoops. Hagia Sophia has survived till our days and I hope it will stand many years more. However, it is deprived of the simplicity and harmony an earthquake resistant building needs and which have been shown by Pantheon.

Let certain disadvantages of Hagia Sophia which are not few in number be discussed.

First of all, the general configuration illustrated in our diagram shows four heavy counterforts weakly interconnected by arches. During an earthquake these counterforts would as if support the whole of the cathedral and take up the dome thrust on the one hand, and, on the other hand, they will oscillate independently, exerting extra loads on the cathedral walls, tending to separate from them. More than that, the counterforts opposing each other have not a common center line and are fairly displaced, and during an earthquake they will provoke some twisting of the building as a whole. Next, those pillars-counterforts have not enough strength. They had leaned over already during laying the girth arches and parted by 65 cm upon completion of the construction work [20]. Most likely, it happened owing to a nonuniform ground bedding. It comes out, that some elements of the building failed before any earthquake, which is intolerable with structures resistant to earthquakes. Note, there are no data on the design of the Hagia Sophia foundation.

Now we shall discuss the principal architectural and structural components of Hagia Sophia, its dome. The rise of the initial dome of the building was very small, about 8.2 m, which is one fourth of the dome diameter. Such a dome generates very much thrust which is intolerable from the standpoint of seismic stability. Most likely, the architect Anthemius was aware of the Syrian high-rise domes producing light thrust, but he was enthusiastic about his artistic conception. The result was that the dome collapsed during an earthquake. The new dome of Isidore Junior (563) was erected in the form of hemisphere. It is 6.3 metres higher than the old one. This is a lightened ribbed dome whose forty ribs rest on the forty window piers which are 2.4 m thick and perform the functions of counterforts [18]. Next, there are four girth arches bearing the dome, they 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 respective improvements at the Byzantine time. An example is as follows. The collar beams of metal in the dome base which had been used before for the erection purposes and were cut off upon completion of the construction work, now were left, after it had been noticed that, taking up some thrust, they add to the seismic stability of the dome.

All building structures may be divided into two large classes by their predisposition to deformation: flexible and rigid. So, by its structure and materials Hagia Sophia refers to the class of hard 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, the Byzantine architects continued their quest for new more perfect structural schemes in compliance with the principles of the synthesized systems mentioned above. Finally, such a structure was found in the form of a cross-vaulted architectural system that is known as the principal achievement of the Byzantine craftsmen [20]. Though, this is a controversial question, since certain authors maintain that the cross-vaulted system has been first used in Armenia [21]. 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 are their advantages and disadvantages to be taken into consideration when constructing in superseismic regions.

Apart from the architectural-artistic and structural details characteristic of an actual building, the cross-vaulted system is as follows. It is an area square in ground plan surrounded by four walls. There are four sufficiently strong supports symmetrically laid out at the centre of this square, which bear the dome representing the artistic and structural centre of the entire structure. The central dome ceils the central cell of the building. The other eight cells formed by the four central supports are generally vaulted. Note, from the standpoint of seismic stability, the whole of the structure is symmetrical with fairly uniform distribution of weights. The only element that affects the general harmony is the central dome 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-vaulted system satisfies in principle the seismic stability requirements. A final conclusion that an actual building is sufficiently resistant to earthquake effects can be made only after examining its structure in detail. The following example will be used to consider the schematic diagram of the cross-vaulted structure.

It may be said that the classical ideal scheme of a cross-vaulted building is represented by the church in Ile-Anderin in Syria, the 6th century (Fig. 35). Referring to this figure, the weights and rigidity in this structure are distributed fairly uniformly with regard to the planes of symmetry. However, the most important of it is that the dome is reliably supported vertically and horizontally. It is vertically supported by four strong pillars, and the rigidity of its embedment in the ceiling is ensured by the adjacent barrel vaults forming a firm cross. In addition, the cross-vaulted system meets one more principle of the earthquake-resistive construction that was called above the skeleton principle by which is meant the closing of vertical and horizontal contours of the structure. We shall not discuss in detail the structure shown in Fig. 35 as it will be dealt with in the next chapter when studying the cross-vaulted dome system of Armenia.

A feature of interest observed in the construction technology of the Byzantine empire consists in laying belts of stone in the brick masonry as shown in Fig. 36. Referring to the same figure of a wall fragment, one can see a heavy-duty arch spanning the gate. The arch was built of four courses of flat-laid brick. Sometimes, just the other way about, courses of brick

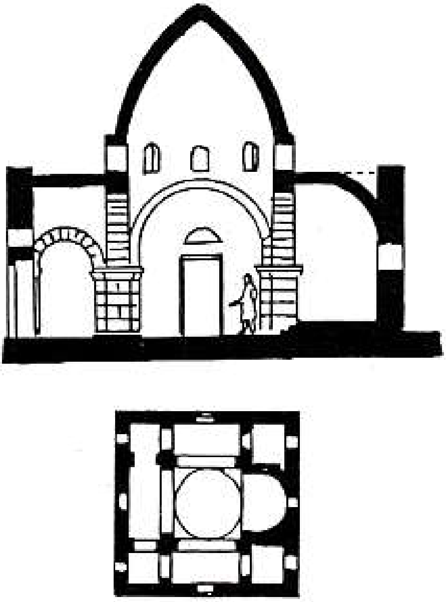

Fig. 35. Cross-Vaulted System

are laid in the stone masonry. Use was also made of thick layers of mortar equal to the brick thickness. All this meant to add plasticity, elasticity and bonding to the masonry.

There existed one more type of outstanding structures in Constantinople and its neighbourhoods. Some of them have survived and exist today which points to their resistance to earthquakes. These are the so-called cisterns performing the functions of typical production rooms (Fig. 37). In some cases these cisterns were used for storing water. More often, however, they were used as storehouses or workshops. Sometimes semi-basement cisterns formed vast platforms that served as the bedding for unique public buildings. All cisterns are similar in construction, and differ only in their floor area always in the form of a rectangle and the number of floors. The vast compartments were ceilled with the

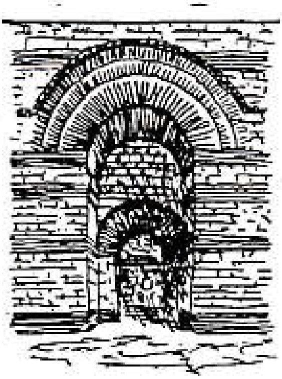

Fig. 36. Superreliable Arch and Reinforcing Stone Masonry with Brick Courses

aid of small span vaults supported by many free-standing columns. In Constantinople there was an especially large compartment of this type, 72 by 65 m in plan area, called Bin-Bir-Direk which meant one thousand and one columns. The cisterns in question were generally 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 combine those arches into a vaulted whole unit for which the arches were used as rigidity ribs. The whole of the firm disk of the vaulted ceiling was tied to the massive rectangle of thick walls used to hold the entire roofing (flooring) against horizontal displacement in case of an earthquake shock, since the columns take up only vertical loads. Like the case was with the other Byzantine buildings, I could not find the description of the foundations anywhere. From the standpoint of seismic stability, we shall treat this important factor as unknown.

Now we shall consider one more, the last, interesting construction design method known in Byzantium. Figure 36 shows a conventional arched ceiling, like that which could be built by Romans. However, sometimes the Byzantines made use of vaults of quite different structure type that could never be used by the Romans.

So, in construction of long structures like aqueducts and bridges, the Roman builders arched the spans between the supports. The thrust thus caused by the semicircular arches was counterbalanced through the supports by the thrust produced by the neighbouring arches. The result was that failure of any support or arch might cause a chain collapse of the neighbouring arches that would be in an unbalanced state then. This situation could not take place in certain Byzantine structures of this type, since they were of quite a diverse design. In their design each half-arch was as if a console of variable rigidity, while the arch itself was split in the key plane. The result is that the half-arches merely contact each other in the split joint without mutual loading. Each support carrying a pair of half-arches is a balanced system and failure of a span has no effect on the strength of the whole of the structure [30]. Note, this structure was used and is used today to construct bridges in mountainous regions in East, say, in India, the Caucasus, and Dagestan [22]. If that is the case, bank and intermediate abutments are made in the form of beams varying in cross-section (Fig. 38) connected by a shortened decking of the bridge which essentially reduces the span bending moment. The resultant structure of such a bridge is resistant to earthquake effects. Independent displa-

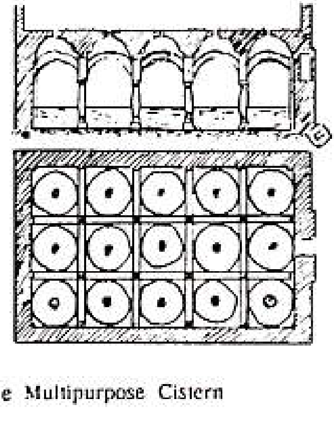

Fig. 37. Byzantine Multipurpose Cistern

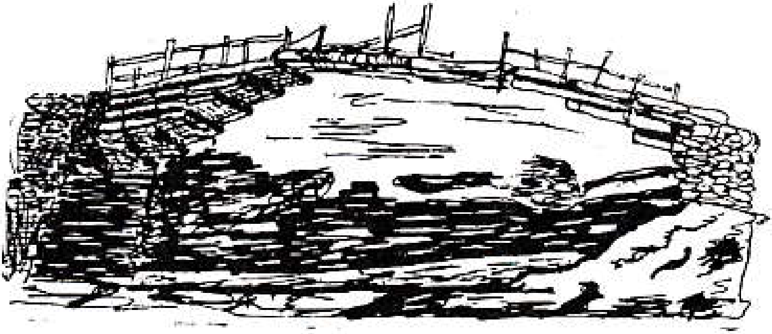

Fig. 38. One of Unloading Systems

cements of the flexibly coupled abutments cause no danger to the bridge structure.

After a short survey of the construction techniques used in the Byzantine empire, we'll go farther eastward, to those countries which were in close contacts with the Byzantine empire, to Armenia and Georgia.

IN THE CAUCASUS FROM THE NOAH'S TIMES

Resistance to Earthquakes of Armenian Temples

Now we are in the Caucasus, the area in which all past civilizations, including visitors from other planets, have left their traces, where there always existed states with their distinctive culture and vast international relations. There is much of interest, earthquake-resistive structures inclusive, in this region, that it is difficult to make choice what to start with. Certainly, it would be best to start with Noah's Ark, a wooden structure which stuck fast on the mountain Ararat in Great Armenia. The Ark was without doubt resistant to earthquake shocks, but there is no enough information about it. We know only her dimensions. We might also start with the state Urartu. Its people established themselves around Lake Van during the 2nd millennium. Their capital was at Van itself, its citadel to be entered only by a rock-cut passage. On the rock faces below were carved Cuneiform inscriptions which supplement the records we have from Assyrians, with whom they were usually at war. The architectural and construction art of the Assyrians was inherited by the Armenian architects. That'll do. Let us begin our survey of the Caucasus, starting with Armenia in the 1st century A.C.

Let us consider the most remarkable structure of the 1st century, the ancient temple of Garni which had a miraculous escape of destruction after Christianity was adopted in Armenia. In 301 A.D. Tiridates III was baptized with all his court and Christianity was proclaimed the state religion. This temple is not an exception, there were probably many such temples at that time, but after the adoption of Christianity as the state religion in Armenia, the heathen structures were destroyed with erection of crosses in place of them. Later Christian temples were built in these sites. Thus, the outstanding monument of the Armenian architecture, the Echmiadzin Cathedral, was built in 303 A.D. in the site of the cross erected in memory of Gregory the Enlightener, the cross in turn being in the site of a heathen temple [21].

We shall not analyse all ancient structures of the ancient 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 defence structures, public baths and temples. One can see somewhat from the time of the early Bronze Age, i.e. the remnants of the structures of 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 the very high construction technology used at that time and highly skilled consideration of its earthquake-resistance imrpovements.

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 column (Fig. 39). But this is only at first sight. The fact is that it harmoniously combines the Greek forms and construction techniques with the mastery of Armenian builders. The Armenians have built their temple of basalt-cut structural members. The Greek craftsmen built with marble and lime stone and could not work with hard basaltic rock. Like in all other cases, we shall start with the foundation.

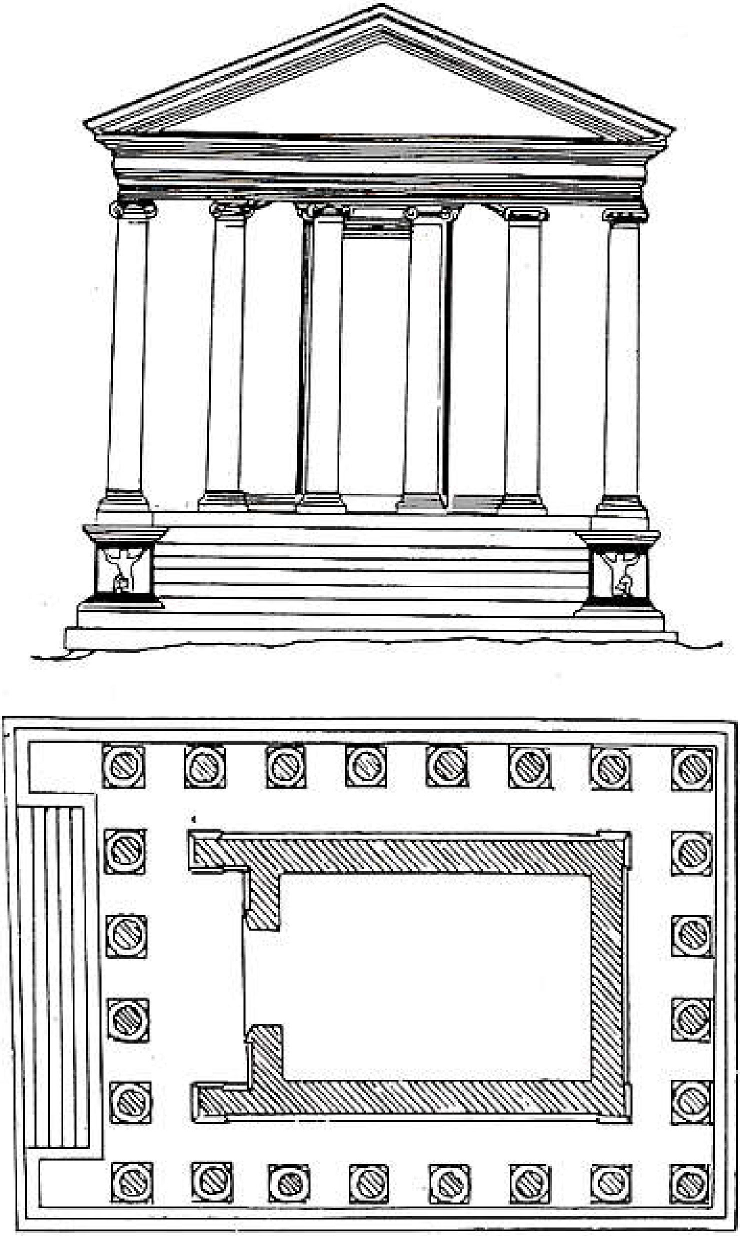

Fig. 39. Greek-Armenian Temple of Garni

The temple is standing not far from a precipice brink, on an inclined rock, which had been levelled with the aid of rubble concrete and sand to obtain a horizontal platform. The thickness of the rubble-concrete course nearer to the precipice was up to 2.5-3.0 metres, tapering away to nothing at the opposite side [23]. The platform supporting the so-called podium of the temple was on a platform made of the same rubble concrete in the East manner. The walls are dry-laid, without mortar, as the case should be with a Greek temple. 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 is equal to the stone width. Note, that the column parts are connected to each other and the floor plate and ceiling by two and three bronze rods, while the Greeks in the cases as these used one central dowel. The ceiling parts are also interconnected by rods and brackets. The work [23] contains fairly convincing evidences that the Garni Citadel had above its central part, a cella, the ceiling in the form of a barrel vault, 5.5 m span, of key stones laid with using lime mortar concurrently with metallic ties. We have encountered this structure of vaults in the Black Sea coastal region Greek settlements. As you remember, the Greeks did not use vaults in the ceilings of their temples. They used light wooden rufters roofings. This citadel was built fully of stone. The space between the cella domes and the flat ceiling of slabs above the side colonnades and the roof had been filled with lime mortar containing light aggregate of volcanic stones. Therefore, the gable surface of the roof was formed by bulk of lightened rubble concrete fully filling the space between the ceiling and the tile roof.

We have considered till now the ductile schemes of the Greek temple type, or the rigid monolithes of the Roman structures. Now, we have encountered a sort of combined scheme which is as follows. Two utterly rigid plates, the lower being the platform of heavy rubble concrete and the upper plate - the ceiling of stone and light rubble concrete, and a ductile supporting connection comprising the columns and walls which is formed by dry-laid stone blocks connected by elastic-plastic ties. In this model of the structure all weights and rigidities are symmetrical with regard to the longitudinal plane of symmetry. The plan dimensions of the structure are moderate, of the order 11 by 15 metres which satisfies the seismic stability requirements. With the described structural scheme of the building, the ductile columns and walls will perform the functions of seismic insulators during an earthquake. The shaking of the lower rigid plate will not be fully transmitted to the upper plate owing to the damping action of the ductile walls and columns. Accordingly, the earthquake loads will be reduced in such a building. As you see, the structural scheme of this building is quite definite, the rigid type of a foundation supporting plate corresponds to a rigid nondeforming ceiling.

In short, a whole set of earthquake-resistive improvements, such as seismic insulation, symmetry, weight reduction due to use of light aggregates in the concrete, elasto-plastic coupling between elements, strength, unloading systems, all these together made the temple standing earthquake shocks during sixteen centuries. The temple collapsed in 1679 during an earthquake, mainly because of the advent of fire arms, the local inhabitants managed to get lead from its joint ties, and thus badly affected its earthquake resistance. If not so, the temple might survive till our time. Perhaps, the main disadvantage of this temple from the seismic-stability standpoint was that it had a heavy roofing taken from the Greek traditions. Not long ago, the temple has been restored so that it can stand earthquakes intensity nine.

We have analysed an outstanding structure built by the Armenian constructors at ancient times and saw the high standards and first-rate workmanship and construction techniques that existed two millennia ago. Now it is time to see what the matter was with the earthquake-resistive construction at the time of the early Middle Ages. An example might be the world-known Cathedral, the still existing Echmiadzin temple, the 3rd-4th centuries, but I think, it's much better to consider a more centrical church of Bagaran which also refers to the cross-shaped dome structures. This church does not exist now, though at the beginning of this

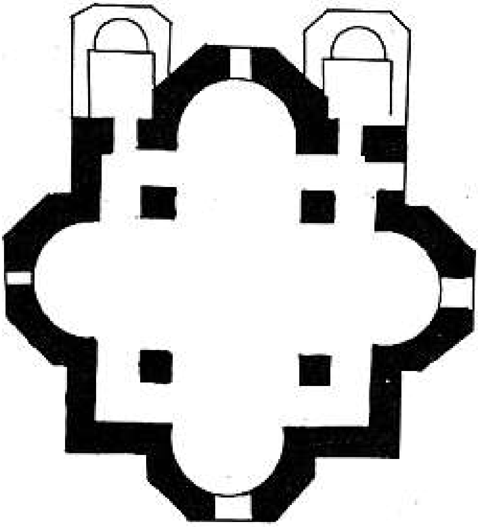

Fig. 40. Centrical Nature of Cross-Vaulted System of the Bagaran Church

century it was in a fairly good condition, only the dome had failed. Being on the Armenian territory passed to Turkey in 1920, the church was completely demolished in the middle of this century [21].

The church of Bagaran was built in 624-631. Its well centrical plan appears in Fig. 40. For its general view, see Fig. 41. As you see in Fig. 41, the church is a three-storey centrical structure [21]. Let us start the study of this church with its plan diagram. Referring to the plan diagram, the church has two planes of symmetry. This ensures the uniform distribution of the weights and rigidity of the church. Note, that the four pillars supporting the dome are widely spread and approached to the walls. This is done to increase the space under the dome. This, however, causes certain structural complications. The arches of the large spacing spanning these pillars and supporting the drum of a fairly heavy dome will 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

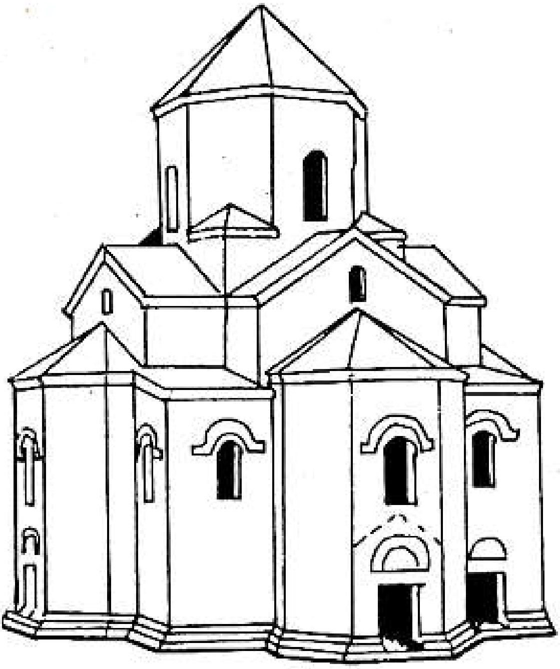

Fig. 41. General View of the Bagaran Church

elements that provided the strength, rigidity, and joint work of the vaulted ceilings of the ground and first storeys. That is what is needed for an earthquake-resistive building.

Referring to Fig. 41, the cross of barrel shells covered by gable roofs 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 borne by the pillars and walls of the church. The whole of the church structure is a unit rigid system. The earthquake resistance of the entire building is dependent upon the strength of its walls, floorings and ceilings, for which reason let us have some talk about the design of walls and domes that were generally used in Armenia in addition to the church we have examined.

Stone is the principal construction material that was at the disposal of the Armenian architects. Times varied, people varied, the techniques of erecting stone walls have changed too. Unfortunately, those changes have not always been positive. Studying the ancient temple of Garni, we have seen that in the 1st century use was made of dry masonry of large stones cut-fitted to each other and interconnected by iron and bronze dowels and brackets sealed with lead. It was only 2000 years ago. And what was the masonry used before? At the pre-Christian times the masonry was made of huge stones of different sizes fairly well fitted to each other. This masonry is called cyclopean. Note, that this "cyclopean" work required much mastery and handicraft, and mainly diligence and workmanship to be able to cut, chisel, move, and fit in place multiton stones of basalt. At the sight of these massive walls of stone blocks accurately fitted to one another, the ancient architect comes into sight as a wise, inventive man with comprehensive knowledge and boundless diligence, rather than a man wearing animal skins and using simple tools. However, with centuries the industry of ancient constructors was diminishing to reach its minimum we are having now. Continuing the study of the stone masonry history in Armenia will convince us of this.

With the first church structures, use was made of three-course nonuniform masonry consisting of two parallel rows of stones with the space between them filled by lime mortar and stones (Fig. 42), and nobody used solid dry-laid masonry of stone blocks fitted to one another. The inner fill of concrete used in the first buildings was insignificant, and accordingly the whole load was taken up by stone. This structure of walls cannot probably provide the required strength, since all inner voids are difficult to be filled with concrete, and therefore the two rows of stones will be poorly bonded and will not work together. Then, use was made of more perfect walls. The stone now is used for facing only and, during the construction work, to serve as the casing filled with coarse flat rubble poured over with lime solution.

The facing plates are chiselled and fitted in place so accurately that no mortar solution is squeezed out. With

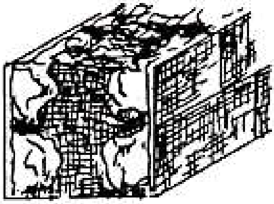

Fig. 42. Three Course Wall

this structure of walls, the load is taken up by the concrete core and even if the facing falls off, the walls remains capable of load carrying. The seismic stability of such monolithic walls having facing plates on both sides has been prooved by many severe shocks of earthquakes that occurred during many centuries. These buildings, as a rule, survived, and if not so, they failed saving large fragments intact [24, 25].

The further improvement was as follows. More savings were made of stone, lime, and labour, and therefore the walls were made thinner and the load was transmitted to the concrete and 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 whole wall width, in every third or fourth course. These walls also well stand earthquake shocks.

Finally, our restless century XX saw the last stage of improving the ancient three-course masonry which is now called the masonry "midis". After the revolution and civil war, at the time of the post-war devastation, the city of Leninakan was being restored. To erect walls, use was widely made of the "midis" stone masonry which as if continues the ancient strong masonry having a homogeneous core of a fairly plastic material and thus being resistant to earthquake loads. Unfortunately, either as to its ideas, or its implementation, the modern masonry has had no connection with that ancient masonry. The idea of the three-course masonry was carried in the modern masonry to the point of absurdity. It was 30 to 40 cm thick. It consisted of two parallel rows of stones with a small thickness of cement used as the bond between them. Bondstones were laid in rare cases. The whole of this structure was unreliable, brittle, of low strength. Correspondigly, the "midis" masonry behaved during the earthquake of 1926 in Leninakan. The walls of this masonry collapsed into individual stones, being very brittle, unable to stand the dynamic effects. After the examination of the consequences of that earthquake, the use of this masonry was banned. Apparently, the human nature was varying like the case was with the stone masonry structure which degraded from century to century. The sorrowful lessons of the earthquake of 1926 in Leninakan were forgot with resultant reuse of the "midis" masonry, though many people knew that it had been banned. Later on much was told and shown how universal was the collapse of the stone walls in Leninakan and Spitak during the earthquake of 1988. Why was the experience of the ancient architects not used? Does anybody know why the lesson of the earthquake in 1926 did no good? These are questions to be replied by sociologists and economists.

The rocky earth of Armenia was too often shocked by earthquakes and her architects could not, but be aware of it. They have devised many improvements aimed at providing the earthquake resistance of ancient buildings. Let us consider some of these improvements.

Like the case was with the Palace of Minos, and the city of Rome, the Armenian architects used squared timbers to reinforce the stone walls and vault bases to make them flexible to perform the functions of seismic-stability belts. Like the purpose of barrel hoops, the function of the seismic-stability belts is to tighten a building into a unit whole. In some Armenian monumental structures the belts are done in the form of stones with hooks run along the entire perimeter of the building.

Like all the ancient buildings, the Jerusalem Temple of the time of ruler Herod including, the Armenian architecture widely used unloading systems above the door and window openings. We may say for sure that the Armenian systems featured improved reliability. There were many of them [26]. There was not a single door without its unique make, though all of them generally were practically of the similar principle.

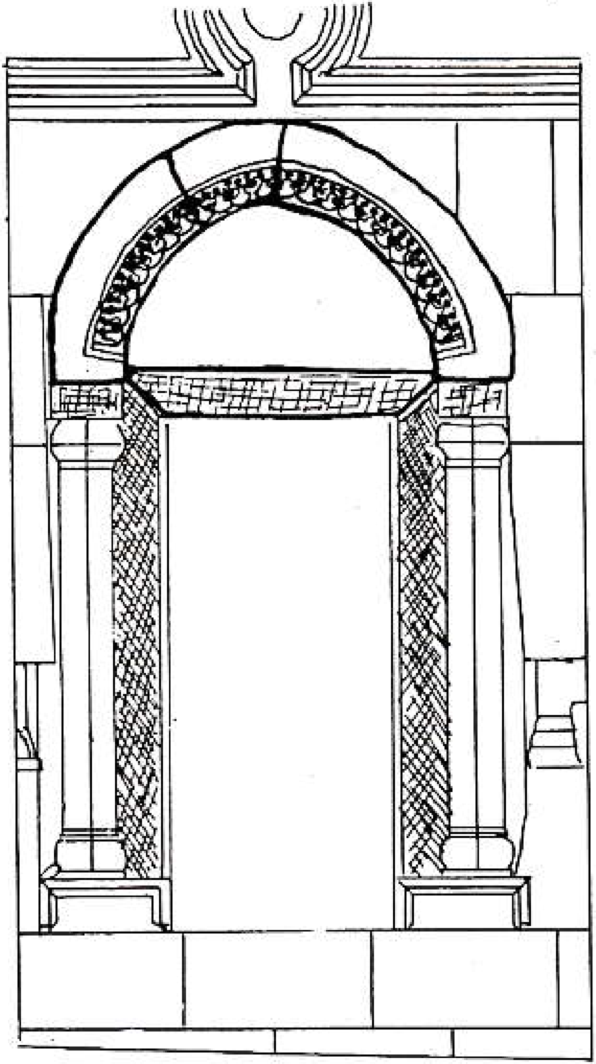

Fig. 43. Portal of the Small Church of Our Lady

Figure 43 shows the portal of the Small Church of Our Lady in the monastery of Makaravank, the 12th century. Referring to the figure, the unloading system consists of two elements. This, first of all, is a semicircle or lancet plate. You see, it is again done in a skilled way, like in the Lion Gate; the plate is thickest at the point wherein the bending moment is greatest, at the midpoint of the span. From the top the above-door plate was protected against the above load by an arch. The design of arches in Armenia has specific features of interest. Though these arches were curved, but they were not built of similar key stones; the builder tried to reduce the number of elements comprising the arch and assembled it of a few curved balks. This added to the reliability of the arch in case of an earthquake shock, reducing its risk of collapsing. More than that, the stones comprising the arch had a tooth to prevent their falling down in case of structure displacement [25].

Now, a few words about the shape of the well-known peaked ribbed Armenian domes. The first Christian churches had wooden roofs, which is good from the standpoint of seismic stability. The stone vaults were substituted for the wooden roofs in the 5th-6th centuries. The roof of these vaulted ceilings was made of mortar-laid tiles. By the 10th century, when the church construction was resumed, after it had been interrupted by the Arab dominion, the tile was ousted by thin stone plates. Tile was convenient to cover any surfaces, curved one inclusive; with use of stone roofs, use was made of cone shaped domes with a straightline generator (Fig. 44). The weight of those domes was far greater and the builders had to show concern for reducing the weight by lightening the dome fill. Embedded in the fill were clay vessels, laying them in turn along the vault, bottom up, bottom down, like it had been done by the Roman builders. The dome was ribbed also to the same end, i.e. to reduce its weight. At the same time, the ribs made the dome stronger and more rigid. During the earthquake of 1988 the temple of the Saviour in the centre of Leninakan collapsed due to wetting the base grounds. The side ribbed-cone domes fell down from a great height and remained intact.

Completing the condensed review of earthquake-resistance improvements used by the ancient architects

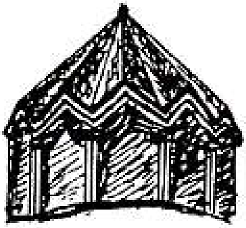

Fig. 44. Ribbed Armenian Dome

of Armenia, I want to dwell upon two more points. First of all the foundations which count much in improving the seismic stability of buildings and about which, except the temple of Garni, I could retell nothing. An old story goes that the temple of Echmiadzin was built on a sand bedding and this made it earthquake-resistive.

Next, in addition to the cross-vaulted system borne by pillars, the Armenian architecture used a unique system of postless ceiling in the 12th-14th centuries. Such a ceiling is structurally based on a couple of intercrossing arches forming a skeleton supporting the dome (Fig. 45). This structure allows ceiling the buildings having a considerable area. Note, that all above-mentioned domes were built together with skeleton systems. All of them have stood well the earthquake shocks. An outworthy example of the Armenian architecture is represented by the temple of Gandzasar in Nagornyi-Karabakh, which concentrates all the people has accumulated during several centuries. I was lucky to be in this temple and was struck first of all by the details. But really, the facing stone plates were precisely fitted to each other, the curved blocks intimately contact each other and form two couples of intercrossing heavy arches carrying the church vault, and the locks of the roof stone plates accurately fit each other. My impression was that if the whole of the building were disassembled into individual stone parts, it would be easy to reassemble the temple, so accurately the stones were fitted to one another, and each stone could be returned exactly to its place. So high workmanship allowed the temple to stand more

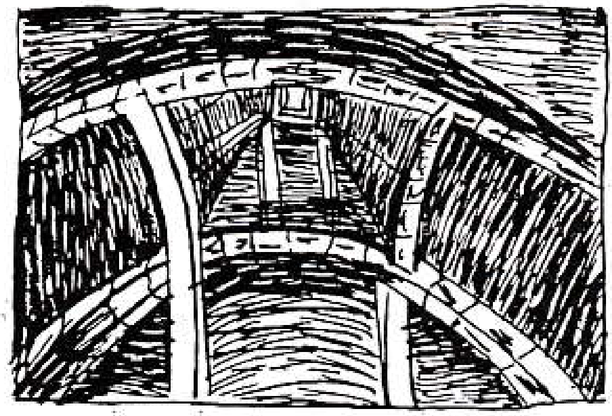

Fig. 45. Arched Skeleton for Supporting Dome

than 700 years without restoration; this was, however, told me by the local comrades. As to me, I can testify to that the temple was far from being an ancient mossy structure with cracked walls and ceiling 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 eastern side. Both these buildings form one structure erected on a five-step platform-stylobate of rubble concrete with lime mortar. The church is ceiled by cross-vaulted system resting on four pillars connected with the walls which provides good stability of the entire system. Lancet arches are spanned between the pillars. Another system was used to ceil the vestibule built somewhat later. Its vault is borne by two couples of intercrossing arches. Besides, it points to the architect being 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 lateral arch. It is not good from the standpoint of seismic stability to erect an arch of unequal rigidity. Neither it is good that the church and vestibule buildings are not separated by an antiearthquake joint. In all the other respects, the building is probably so good that the temple of Gandzasar has been standing more than 700 years with no damage. Finishing writings on the earthquake resistance of multiple ancient monumental structures of Armenia, it is difficult to keep from telling about one more Armenian temple, a wonder either of East, or West that can be dreamed about only in sleep. This is Zvartnots, the Temple of Vigil Forces, the construction of which was started in 643, the money being collected by the people. For the general view of the temple, see Fig. 46.

Its ground plan appears in Fig. 47. The temples of this style were built in East, but there were a few of

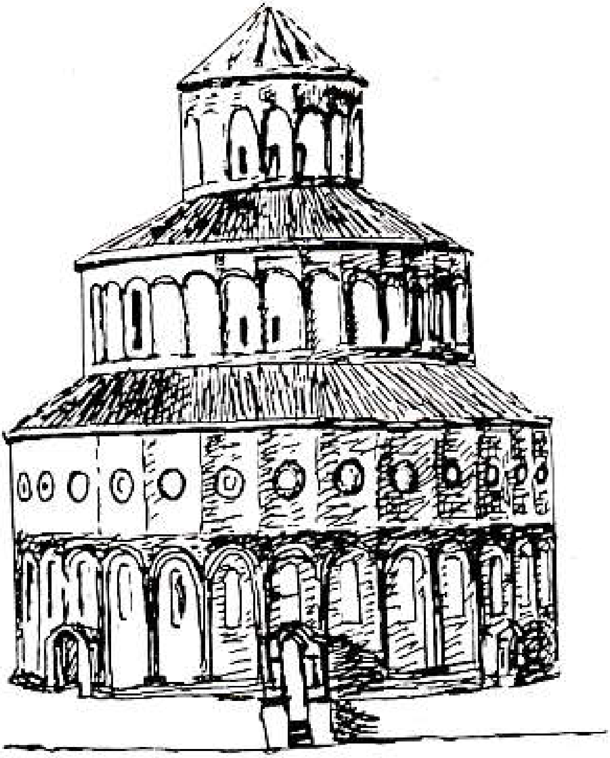

Fig. 46. General View of Zvartnots

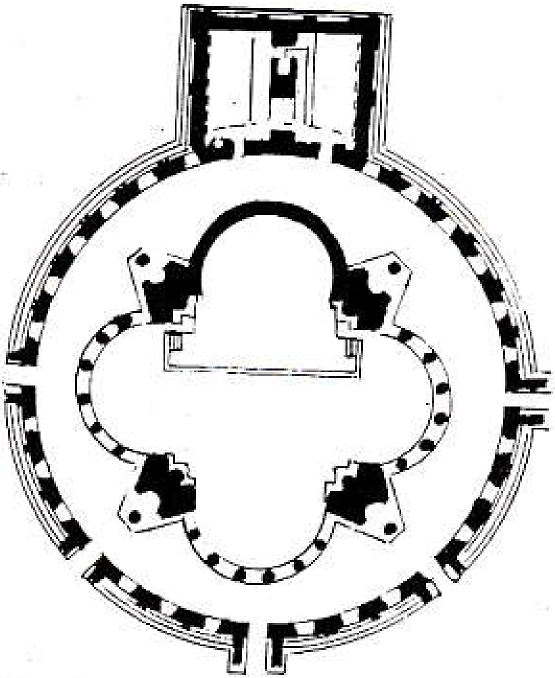

Fig. 47. Ground Plan of Zvartnots

them, and the temple of Zvartnots was unique both in form and design. It survived more than 300 years and collapsed, as it is considered, at the end of the 10th century due to an earthquake.

Let us analyse in short the unique structure of this temple. Referring to the figure, it is a centrical building consisting of three barrels placed on each other. The lower barrel is about 36 metres, the middle one, about 26.0 metres in diameter, and its total height is about 45 metres. It is well thought over in the temple structure to properly transmit and distribute the loads. The first largest and highest barrel was formed by round wall (Fig. 47). The second barrel smaller in diameter rested on a ring laid of stone and lime mortar. The top view diagram of this ring appears in Fig. 48. This element of the structure is of utmost

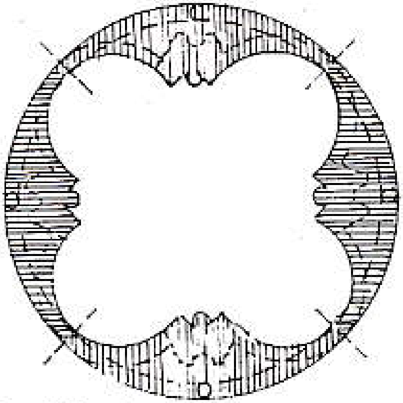

Fig. 48. Base Ring of Temple

interest. The ring is 82 m in the outer 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 withstands where stone does crack. The ring itself rests on the four pillars which pass through it and support the top small barrel having a cone dome. In addition to the pillars, the same ring also rests on all columns of the ground storey to connect them to each other. This strong ring forms the key element of the whole of the structure. First, it supports the second (from the ground) storey; second, it is the earthquake resistant belt connecting the spatial system including pillars, columns and the walls of the ground storey into a unit whole. The entire structure of Zvartnots turned out a light and proportional building, the more so that the builders tried to lighten the building as much as practicable, using tufa and pumice-stone as concrete aggregate and embedding hollow pots in the walls carrying loads.

Some components of this temple are of interest too. Examples are columns that were made of three elements: the base, the shaft and the capital each of them being made of solid stone. Metallic cramps were used to connect them together, the cramps being lead sealed. This was a traditional ancient technique. The columns turned out plastic and worked only into compression.

Disadvantages of this structure may be noted as well. There is no uniform rigidity distribution at the level of the ground storey. Referring to Fig. 47, as if a tower is attached without joint to the barrel of this storey through its entire height to house a stair leading to the top gallery. Certainly, it somewhat affected the uniformity of weights 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 the case is with Pantheon, and protrude beyond their plane at least two metres. It is clear, that this shape of vaults will cause their twist which is far from being 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 350 years [27]. Some investigators try to find out the causes of the Zvartnots failure. What were mistakes? Maybe the quality was poor, maybe the pylons of 22 metres were a bit longer than ought to be, maybe the columns were of insufficient strength, and maybe there was some other cause. I agree with the work [27] according to which there were no mistakes. Everything had been well thought over. The only factor that affected the temple was the three-century dominion of Arabs during which the temple fell into decay. During this time there was a fire; maybe it was used as a stone quarry, or maybe the general mismanagement has led to the collapse of Zvartnots.

Generally, it is not correct when we, their descendants, speak of mistakes made by the ancient builders. We say that Zvartnots stood merely above three centuries, surviving all earthquakes occurred during that period, and then collapsed. At the same time, during the earthquake of 1988 in Armenia, many buildings less than three years old collapsed. In addition to bad quality, there were committed most gross errors in the design documents. An example is a series of five-storey dwelling houses which suffered most from this earthquake. These buildings did not

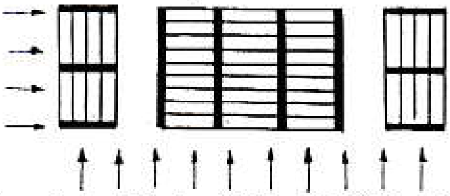

Fig. 49. Plan of Load-Bearing Walls of Buildings That Collapsed During Earthquake of 1988 in Armenia

meet the principle requirements of earthquake-resistance construction: the rigidity and weight were not equally distributed in the building. The plan in Fig. 49 shows the layout of the load-carrying walls in those five-storey dwelling houses. It also shows the position of the flooring and ceiling slabs. How does a separately standing wall stand to loading? It can stand to loads only in its plane and almost can not withstand perpendicular loads. To increase their resistance to loads, the longitudinal and lateral walls are usually interconnected by anticarthquake belts to form closed contours. This was not provided in the buildings in question. The longitudinal walls of the end sections were not tied to the lateral walls of the central section of the building. When a building was attacked by a front earthquake wave (*1* in Fig. 49), the building end sections failed because the wave destroyed those walls that were perpendicular to the wave direction of propagation. If the earthquake waves were propagating along the building (*2*), the building centre collapsed. If the building was attacked by a wave at an angle, the entire building might collapse which was frequently the case. As distinct from Zvartnots, there was no integrated rigid disk which would provide joint work of walls of different directions. So, we may criticize the ancient architects, but it is more important that we learn from them, and we have much to do so.

Let us continue our excursion to the Caucasus. We shall not visit Georgia, though there are also many monumental structures of much interest, but the construction technology is about the same, therefore we are not much interested in this region. At the same time, the North Caucasus deserves some study. I wish you are acquainted with certain construction traditions of people.

While the essential temples in Armenia and Georgia were erected by highly educated and skilled architects, the watch and household towers in the North Caucasus settlements were built by the craftsmen familiarized with the traditions only of this region. Here we also have much of interest.

Towers in Mountains

Construction of towers in the Caucasus have been known for a long period of time. There were defence, dwelling, chapel, and mausoleum towers. Stone was the principal construction material. Lime and clay were mortar materials. Of all structures in the mountain settlements the towers, the defence towers in particular, were unique structures. These were built of large well selected stone blocks by the best craftsman. 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 the stones of an entire settlement. The materials were thoroughly selected; weathered, cracked stones were rejected. The towers were expensive, though they were built of local materials and by the local craftsmen. The towers could be erected only by well-to-do families. The towers were mainly rectangular, seldom round[1], though the advantages of round towers from the standpoint of defence are incontestable. The same was good for the earthquake resistance construction. Naturally, the rural craftsmen did not use any particular antiearthquake improvements, they met this requirement by making their structures strong and stable, using the historically evolved traditional architectural forms. I was always delighted with these towers surrounded with legends and romance of blood feud; with all their simplicity they are pieces of true architecture. Here are some examples.

In the Daghestan village of Itsari there stands a watch tower in the form of truncated cone (Fig. 50) which is unusual in these localities. It was erected in the 15th century by the local inhabitants, when their prince transferred his residence from their village to

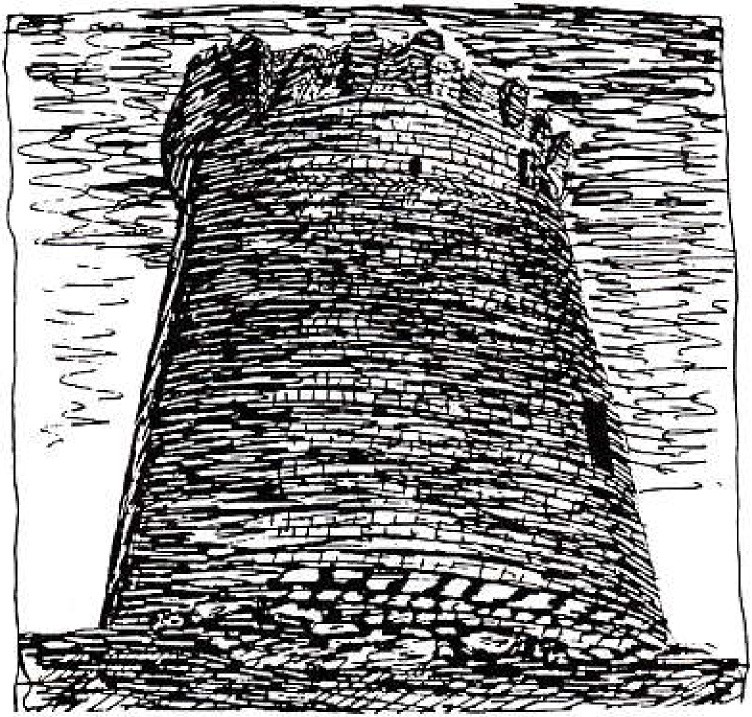

Fig. 50. World Wonder of Local Nature

another site, and the village inhabitants had to rely solely on themselves. The tower shape and technique of laying stone materials point to the fact that its builders 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 weights 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 provide 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.

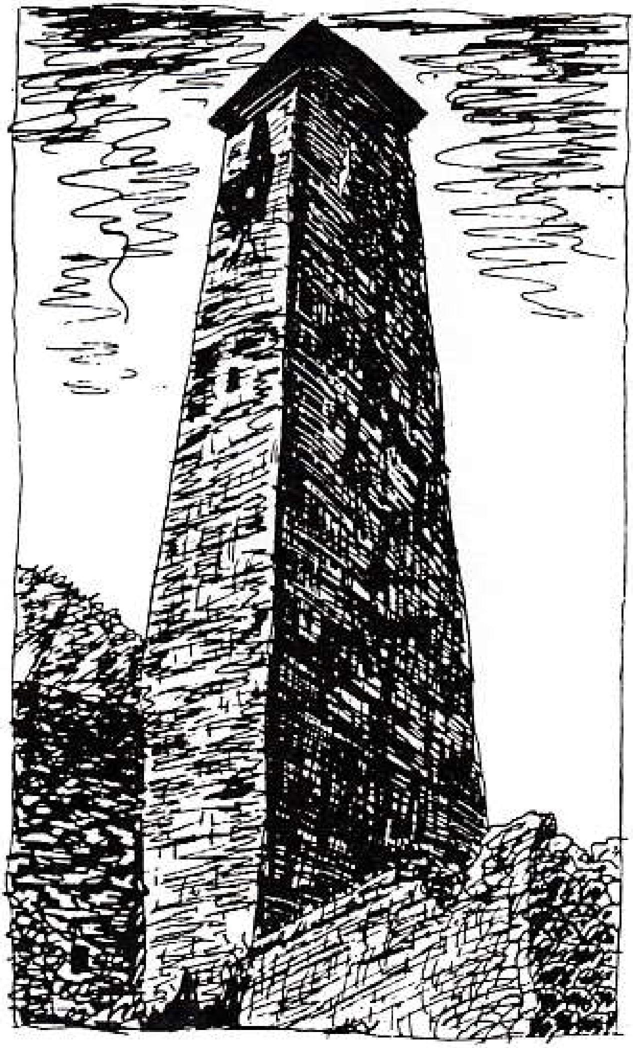

Fig. 51. Vaynakh Watch Tower. General View

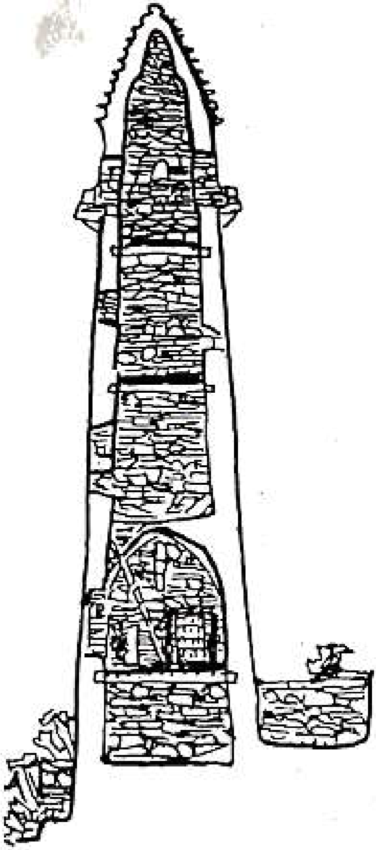

Fig. 52. Vaynakh Watch Tower. Cross-Sectional View

The Vaynakh watch tower of the classical type is shown in Fig. 51. 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 walls of these towers were laid in a very complicated manner. The wall thickness decreases with height with simultaneous inward inclination of the walls. As a result, the tower silhouette shows clear narrowing. To my mind, whatever the motives were, the tower builders tried not only to provide the symmetry of the

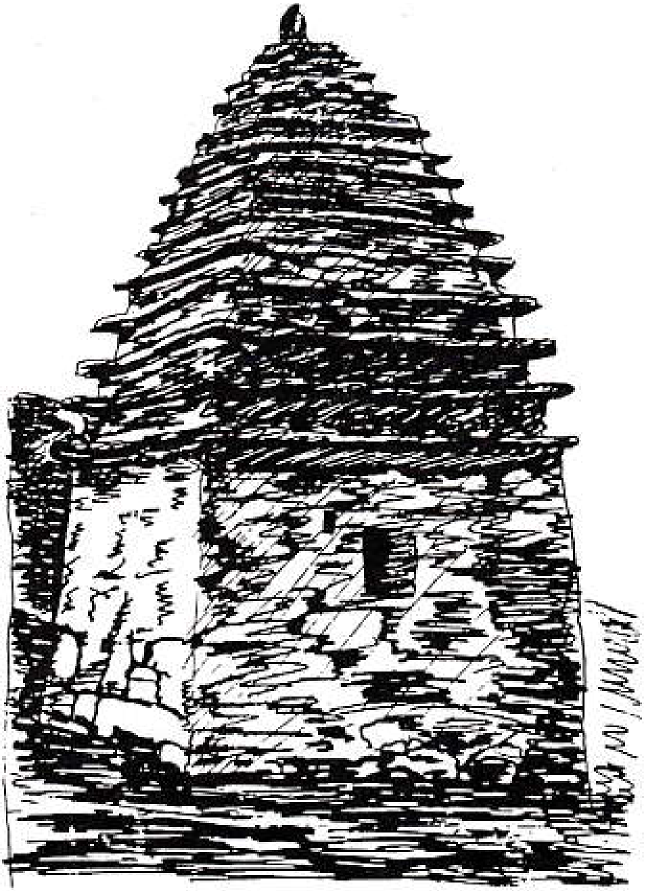

Fig. 53. Pyramid Tomb

tower, but also to reduce the tower weight, and to lower the tower center of gravity, and thus to make the structure earthquake resistant.

The lime mortar used in the masonry work was sometimes very strong. In Daghestan use was made of clay mortar 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 which improved their architecture and protected them against elements (Fig. 52). The floors were also made in the form of a closed four-sided pseudo-vault by corbelling the stones which created rigid disks along the height of the tower. These disks also performed the functions of seismic-stability belts. It has turned out that the Vaynakh towers met almost all the requirements of earthquake-resistive construction. The other towers used wooden floors and they were not perfect from the standpoint of seismic stability because of diverse causes such as weak mortar, heavy walls, nonuniform masonry, absence of rigidity disks, and even unreliable clay roofing.

The traditional tombs found in groups and separately in the mountains of Ossetia are remarkable for their appearance and fairly perfect in their structure (Fig. 53). These are small square (in plan) structures whose walls are slightly inclined inward and gradually turn into a high vaulted roof. Stone plates protruding outside were fitted in the joints between the stones of the vaulted roof, which makes the Ossetian tombs look somewhat like the multistorey pagodas of Indochina. Generally, nearly all rudiments of the construction techniques can be found in the traditional popular structures which later on are improved and used in the monumental construction of palaces and temples, providing their strength and long life. These are strong walls and foundations, use of various unloading systems, erection of vaults and many other factors. So, the popular and monumental constructions are of the same origins. To continue our jorney, we'll set off for the Trunscaucasian plains.

Lights and Towers of Apsheron

Earthquake storms occurring in the depths of the Caucasian mountains shake this large plain representing the central area of Azerbaijan. On the three sides this plain is surrounded by mountain ranges. On the eastern, fourth side the plain is washed by the Caspian Sea with its peninsula of Apsheron deeply plunging into the sea. Variety of natural resources, much stone in the mountains, clay in the plain, their own historical traditions, another religion, all this gave rise to other architectural and construction tasks and their specific solution suitable for these areas. Certainly, there are signs of. relations with other peoples of the Caucasus, but we also can see traces of fairly close relations with peoples of Central Asia. People settled on fertile soils of this plain long ago. Found are settlements of settled cattle-breeders built in the 6th-4th millennia B.C. These settlements were built of round vaulted cabins of air bricks [31]. The accumulation of construction experience started at that time. We shall not examine so ancient ages. We shall not deal even with the tribes who settled in the territory of Azerbaijan lying between the Black and Caspian Seas in the 9th ccentury B.C. These later created a state that fought against troops of Alexander the Great. Midia was one of the fire-worship centres and had relations with Assyria, Babylonia, and Urartu. It is the region from which the architecture of the structures we shall consider further originates. In our study we shall take separate monument structures and examine them from the standpoint of earthquake resistance.

We shall start with the Virgin Tower which can be admired in the city of Baku (Fig. 54). The tower greatly differs from the other defence and religious structures of Azerbaijan. It is fully mysterious. According to one historic work [3], it was erected in the 8th century B.C. According to another not less historic work [2], it was built in the 12th century A.C. As to the purpose on the one hand it was as if a tower-type temple of fire-worshipers, on the other hand it had been built to provide concealment for the citizens of the town when an enemy was approaching the town. Hence the name Virgin, since it has been never captured by any enemy. The purpose of its counterfort is absolutely unknown. It is asymmetrically attached to the round tower. The list of unintelligible facts could be continued, but thank God, this is not our problem. We are interested in 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 metres. At the sea side, its height is 35 metres. Referring to

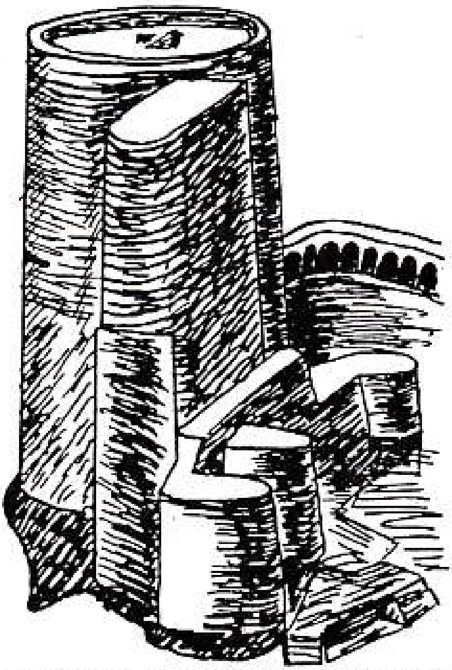

Fig. 54. Asymmetry of Tower-type Temple of Fire-Worshipers

the figure, a heavy strong counterfort is attached to the tower at that side at which the tower could slide down along the inclined rock. The counterfort, in turn, is supported by a wall with small counterforts. It points to the much concern for the stable base of the tower shown by the ancient architects. The tower walls are unbelievably thick. Their thickness ranges from 5.0 m at the foot to 4.0 m at the top. The walls are laid of limestone with use of strong lime mortar. The internal space of the tower is divided into eight storeys by plain stone domes. The specific ribbed external surface of the tower is formed by the alternation of jutting and sunk courses of masonry [2].

It follows from the above-said about the tower structure that the tower is a very rigid, extremely heavy solid mass with uniformly shared weights and rigidity, except for the counterfort. In fact, this side

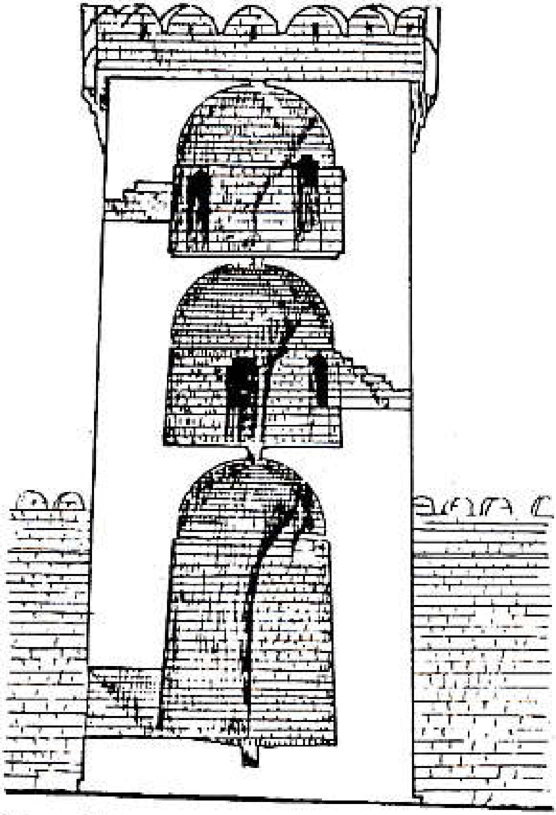

Fig. 55. Design of Massive Stone Watch Tower

counterfort may be neglected, since its twisting effect in case of an earthquake is impossible due to the immense thickness of the tower walls and hence so huge a twist-resisting moment. In short, despite of the completely diverse materials and structures, this tower resembles the immensely heavy Egypt structures, which accounts for their mysterious resistance to earthquake shocks.

Now, we shall have some talk about conventional watch towers many of which were scattered over the peninsula of Apsheron with a view to protecting the nation's wealth against external enemies.

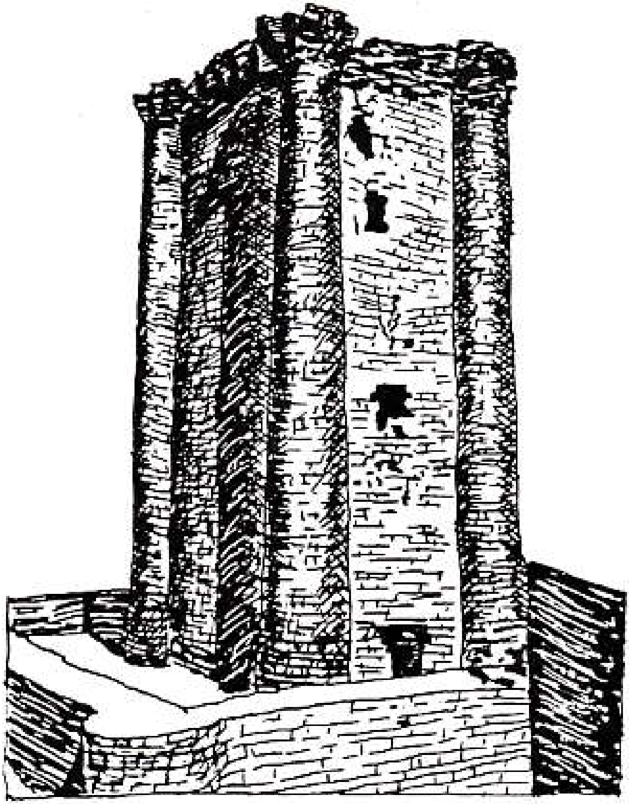

Fig. 56. Rectangular Watch Tower

Survived in a settlement named Mardakyan is a recently restored round tower in the form of a truncated cone, 16.0 metres in height, 7.6 metres in the foot diameter, whose sectional view is shown in Fig. 55. The tower is laid of the local limestone on a highly strong mortar. Referring to the figure, its internal space is 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.

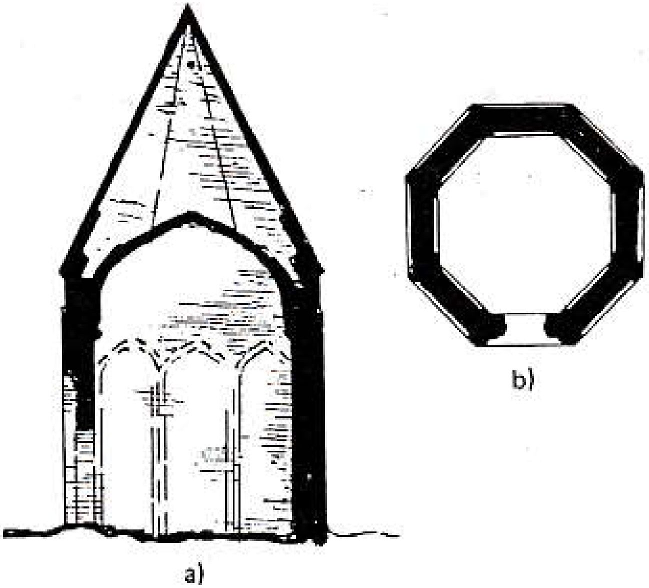

Fig. 57. Centrical Nature and Architectural Harmony of Yusuf Mausoleum

Later they had taken to build rectangular towers in castles. A rectangular castle reinforced by round columns at the corners built in the 14th century has survived in the same settlement of Mardakyan (Fig. 56). In this case, use is also made of stone masonry on a lime mortar, but the internal floors are made on the basis of timber beams [2]. In the above-mentioned defence structures the resistance to earthquake shocks is ensured by their fairly moderate dimensions, symmetrical distribution of weights and rigidity, strength of masonry; in that, weight reduction, and the more so seismic insulation being out of question. Next, let us consider some memorial structures of more complicated design in compliance with the more complicated architectural forms.

In 1162 the construction of the burial-vault for khoja, the head of sheikhs, Yusuf was completed. A sectional view and plan of this burial-vault appear in Fig. 57, while its general view is shown in Fig. 58. We see a conventional structure of that time, but how perfect it is in its design and workmanship. As the architectural proportions and resistance to earthquake shocks are concerned, the mausoleum is perfect. It is built of burnt brick on a strong mortar. Note the octahedral plane of the mausoleum. This is almost ideal form from the standpoint of the resistance to earthquake effects. The walls are of moderate 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 a lancet arches. The wall above these arches is thickened forming a support ring for two domes, an external octahedral and an internal lancet dome. The octahedral walls smoothly develop into an octahedral dome. The generalizing principle of earthquake-resistive construction stating that the building must prevent stress concentrations anywhere during an earthquake has been met herein. The whole of the mausoleum is a rigid structure.

I would like to draw your attention once more to how the ancient builders combined their knowledge, the use of traditions accumulated before, and creative approaches to the structure they were building. A curious example is a fanciful mausoleum of the 12th century, unlike anything, which is standing near a settlement named Jijimli. 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. 59.

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

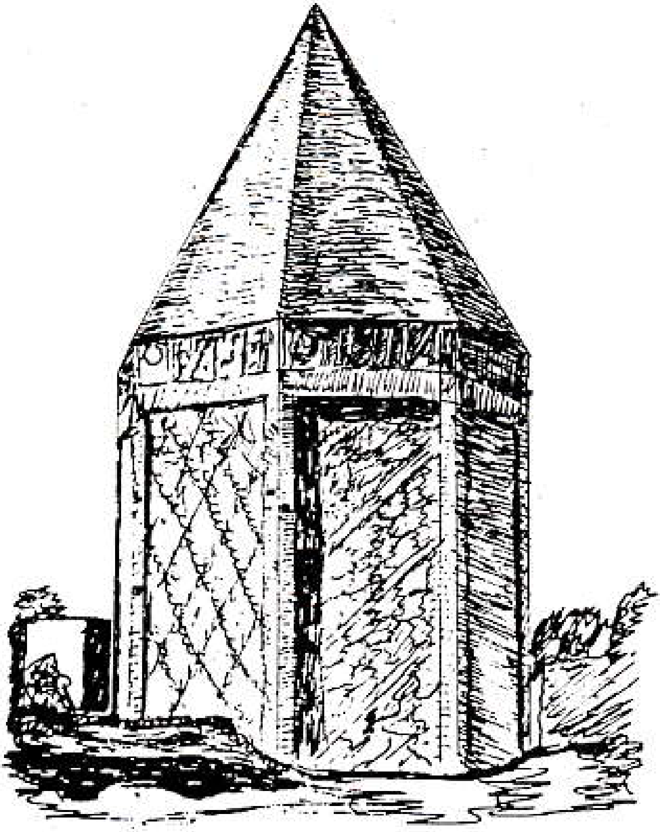

Fig. 58. General View of Yusuf Mausoleum

As the next step, we shall consider a more complicated structure of an intricate design. The unique structures of Azerbaijan were erected up to "world standards", as could be said today, with knowledge of the advanced construction technology of that time. I have already said that, studying the ancient history, one does not stop being surprised at the information knowledge of, it would seem, most remote peoples, particularly, in the field of construction technology. An example of this respect is a monument of the Azerbaijan architecture, the mausoleum of Oljaytu

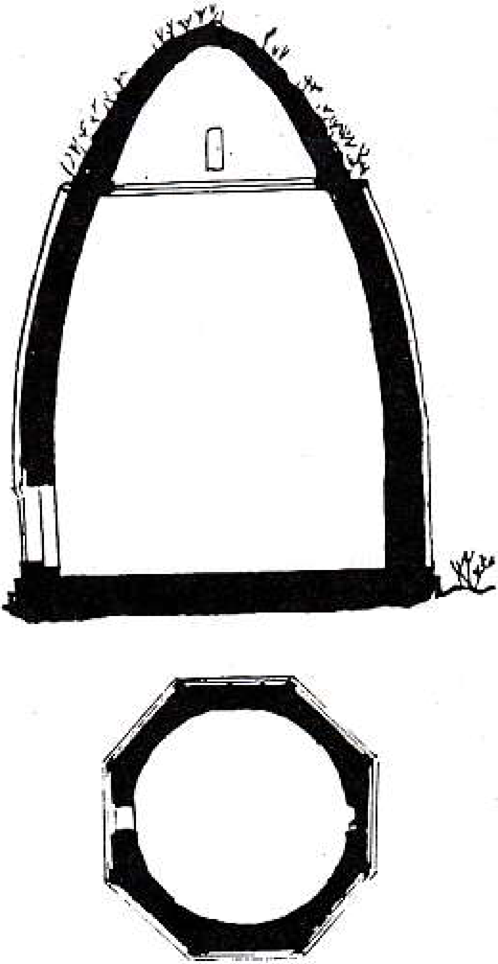

Fig. 59. Shell of Melik Azhdar Mausoleum

Khodabend (1307-1313) [2]. It is a most distinctive outstanding monument of architecture, and at the same time, it has absorbed much of the best created by that time in the construction technology.

Shown in Fig. 60 is a sectional view of the mausoleum built of brick. First that attracts your attention in the figure is the high lancet dome composed of by 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 lock is 51 metres, i.e. it is almost a gigantic structure. The lancet shape of the dome and its double shell with connecting ribs forming a skeleton system resemble both the dome of the Florentine cathedral and the dome of St. Peter's Basilica talked 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 the dome strength and rigidity. Note, that the mausoleum in Sultaniya, built long before 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, which is a greater achievement of the builder of this mausoleum. The next important point associated with the seismic stability of the dome roofing is in the smooth joint between the dome and the walls. In this mausoleum this problem is solved in a brilliantly simple way. The huge hall ceiled 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, there is an antithrust monolithic ring reinforced by three metallic hoops in the lower part of the dome. Second, the probable thrust was supported by the vaults of the gallery encircling the base of the dome. In addition, the mausoleum corners were additionally loaded by minarets, which is also an antithrust improvement. The vaulted galleries in the base of the dome are already techniques widely used in the building of Central Asia, for example, in the mausoleum of sultan Sanjar in Old Merv.

The result is that in the mausoleum in question, use has been made of the entire set of the improvements intended for taking up the thrust of a fairly large dome. These are the lancet shape of the dome, a double lightened dome, a reinforced support ring, a smooth joint between the dome and the walls, a

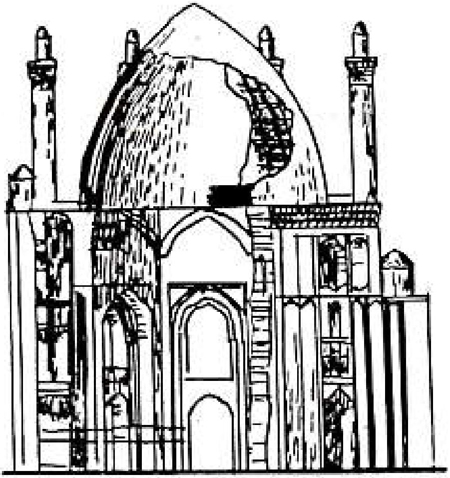

Fig. 60. Complete Set of Aseismic Improvements Used in Dome of Oljaytu Mausoleum

vaulted encircling gallery, additional loading by the minarets. Even at our time we could not do more. The dome of the mausoleum in Sultaniya is still surviving.

The following we are interested in can be added to the structure of the mausoleum. The dome rests on the walls in which brick arches are embedded, like in Pantheon, but now in the lancet form. Again like in Pantheon, the walls are lightened by deep niches also vaulted by lancet arches of brick. This is an example of high construction art obtained by the Transcaucasian architects achieved many centuries ago [2].

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

We must mention the famous "Long walls" built in the north of Azerbaijan to protect the plains of the Caspian Sea region against the northern nomads. The gigantic defence structures of Derbent were built of large stone blocks, using lime mortar, in the 6th century. Their purpose was to close the Caspian passage between the mountains and the sea. The stone masonry of the walls and towers of these defence structures was usually made of two parallel stone walls, the space between which was filled with rubble masonry on lime mortar. The stone walls were dry-laid of stone plates tightly fitted to each other and alternately laid stretcher and header courses, which provided good bonding between the facing and fill. Such three-course defence walls up to 3.0 metres in thickness and 12 meters in height well stood both ram blows and earthquake fources. Note, like the case was with the Byzantine defence structures, the towers in Derbent were erected wall-to-wall but without bonding between the tower and wall [2].

Other seismic-stability improvements of that time may be called here. The brick masonry was reinforced by timber beams. Timber beams were also placed above the entrance apertures. We have already talked about the purpose of all that.

Along with the lime mortar, use was made of looser mortars (locally called "gyazhevye" mortars). The lime mortars are harder and more brittle than the looser mortars which are more plastic and thus stronger. It must be also said, that the cement mortars are still more hard and brittle than the lime mortars. Naturally, when it was necessary to impart ductility to a brick or stone masonry, use was made of looser mortars. In this case, the thickness of the bedding joints between the brick courses, was essentially increased. This purely aseismic technique was widely used in the architecture of Central Asia. Use was also made of brick belts in the stone masonry, as it had been 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 one end of the ceiling arches, while the other end of the arches rested on the walls.

Having received some knowledge of the earthquake-resistive construction of ancient Azerbaijan, we shall continue our investigations further in Central Asia with which it had close relations. Examples are splendid mausoleums decorated with heavy portals which appeared in the 14th-15th centuries, under Tamberlane, Timur Lenk, and his descendants in Central Asia. These portals affected the centricity of those structures and reduced accordingly their resistance to earthquake shocks. At the same time mausoleums with attached portals appeared in Azerbaijan.

SEISMIC STABILITY WONDERS IN CENTRAL ASIA

Prehistoric Times

We have reached one more region of this sublunar world including vast areas, having complex history, and possessing diverse traditions. The settled agriculture began in Central Asia still in the 5th-4th millennia B.C. Small settlements appeared in oases, copper smelting took place, contacts with Sumers were established. In the 3rd-2nd millennia B.C., an association formed in the south of Central Asia. The culture of that association was conventionally called Altyn-depe. Of the monumental architecture of that time we know a large religious complex dedicated to the Lunar God which included 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 the other oases of Central Asia, was joined to the Persian empire of Achaemenids.

The empire of Achaemenids was finally overthrown in 331 B.C. by 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. Henceforth, 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'll continue studying our narrow problem of the seismic-stability improvements used by the ancient architects. To this end, we take some historic facts we are interested in and analyse them from the standpoint of modern earthquake-resistive construction. Like the case was with the Caucasus; we'll start with the 1st century A.C.

Let us start with the site of settlement known as Toprak-Kala situated in the Lower Amu Darya region. This archaeological complex comprises a well fortified town, a palace on a high platform, one more palace block, a fortress, and a mysterious vast area surrounded by a bank. These are the remains of the capital of the Khoresm kings. The very first, most active period of this capital existence, was in the 1st-3rd centuries A.C. Of many buildings of this town we shall consider solely the high palace standing on a gigantic platform. This will be enough to understand the construction technology of that time.

Studying the structures of the High Palace, there seems to be an impression that we have returned to the valleys of Mesopotamia, wherein adobe brick of loess clay was the principal building material; buildings were erected on special platforms, and wherein the use of vaulted structures was started. In Toprak-Kala, like in the other monumental structures of Khoresm at that time, the principal building material was represented by adobe brick of loess clay. All load-bearing structures were laid of this brick. Use was made of two types of brick. The first, most popular, was the plain square brick, 40 by 40 by 10 cm in size which was about 8 times the weight of the present-day brick and weighed about 38 kg. This brick was used to lay platforms, walls and beam ceilings. As a rule, the brick made 57 per cent of the total volume of masonry, 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. It found its applications in erecting arches and vaults. In addition to the shape, this brick differed from the former type in composition which had effects on its mechanical properties. Chopped straw was added to the 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, the better brick was used in the 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 platform, up to 14.3 m high, which was in the form of a regular rectangular truncated pyramid. The area of the bottom base is 92.5 x 92.5 m, the top area being 82.5 by 83.1 m. To illustrate the size of the platform, I can say that about 6 000 000 of those huge bricks were used to build it. The platform was multipurpose. First of all, it was used for defence purposes, then for protection against floods, for extolling the king's palace and, finally, what is most important to us, for protecting the structures errected on this platform against earthquake waves. The buildings of the Low Palace are also built on platforms, admittedly, on platforms not so huge. Now, some words about the seismic stability elements of the structures of the palace on the platform. A sectional view of the palace, foundations under it and platform is shown in Fig. 61. The truncated pyramid shape of the support platform under the palace adds to its resistance to earthquake shocks. In addition, the platform is embraced along its perimeter by a heavy strong wall of brick bonded by clay mortar. The central part of the platform is represented by coursed substructures of brick on sand and clay. Recall the coursed substructures of Colosseum. Next, laid under the inner walls are ductile cushions of brick on sand which protect the walls against unequal settlements and against earthquake shocks. To provide its seismic stability, the outer wall has paired projections at 1.8 m spacings. The ceilings of the palace are as follows. There are encountered two kinds of ceilings in the palace: a flat ceiling on timber beams and vaulted ceiling of brick specially prepared for the purpose. Interestingly, vaults in the form of ellipse or close to this shape were characteristic of the buildings of Khoresm of that time. To make the vaults more

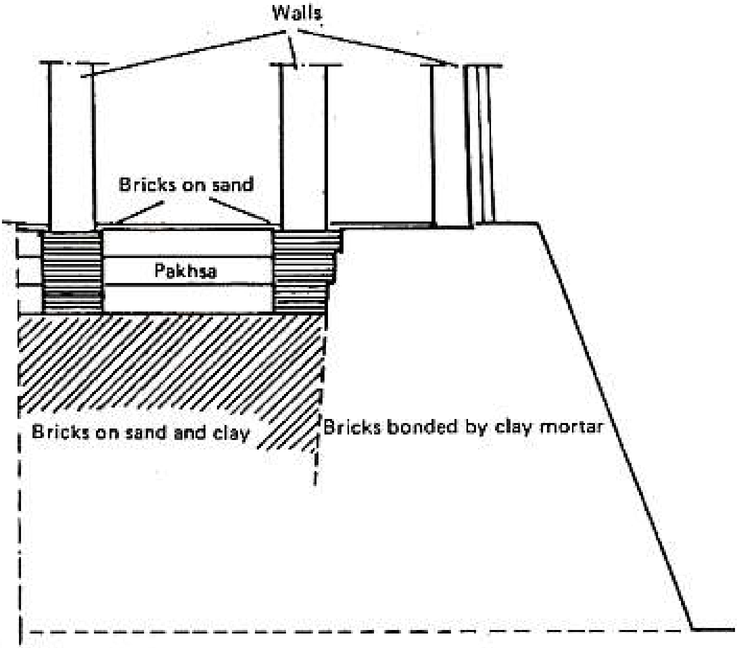

Fig. 61. Seismic Insulation of Adobe Brick Wall of Toprak-Kala Palace

reliable, they were laid in a few rows which allowed some vaults to survive till now. Burnt brick was used as a facing material already at that time [29].

If we wander over the ruins of the High Palace hall a bit more, we are likely to encounter something else we are interested in. Look here, a course of adobe bricks is exposed, and each brick shows traces of the human hand. The craftsman made furrows with his hooked fingers on the side of the formed brick. It was done to improve bonding between the bricks. This is like what the Greeks did roughing the joint surfaces of blocks. Note one more, the last fact. It has been said above that flat ceilings were used in the palace. In case of short spans, timber beams were spanned from a wall to a wall. Next, a counter floor of poles was laid on them, and then there was laid a course of cane coated with clay reinforced by straw. And only then

Fig. 62. Stone Base of Wooden Column

there were laid a course or two courses of clay bonded bricks. This completed the flooring (ceiling). In case of larger spans, the ancient builders erected intermediate supports, columns with stone bases. These stone bases (Fig. 62) 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 stone bases for wooden columns of a similar type can be encountered in the Caucases, and we shall encounter them later in Central Asia. We shall not spend time among the most ancient buildings of adobe brick and go over to more perfect buildings of burnt brick. We shall not deal with stone structures in Central Asia, as they are very seldom.

Set of Measures Taken to Resist Earthquakes

Within even your memory the lands of Central Asia were many times shaken by earthquakes, and during their turbulent history these lands underwent many catastrophic earthquakes, which is testified to by instantly destroyed towns buried under sands. Naturally, the ancient craftsmen persistently searched for methods to protect their structures against earthquakes and had developed a series of structural improvements to provide seismic stability of their creations. To be fair in our judgements, we must say that they found nothing new. The architects of Central Asia arrived at the conclusion similar to those of all other their contemporaries and predecessors: only elastic and strong materials are capable of standing earthquake shocks, provided certain rules for composing structure components are followed. Recall the builders of the Knossos palace who imparted ductility to their rigid stone structures by reinforcing them with timbers. The seismic-stability ideas of the architects of Central Asia were similar to those of all architects, but the structural implementations of their ideas were specific. Without associating for the time being with almost any actual structure, I'll try to mention typical seismic-stability improvements used 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 the ganch for its strength and plasticity. The ganch was prepared from the local alabaster by firing, subsequent grinding and sifting. The 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 it was mixed with other components still in the dry state, with loess, sand, charcoal, and with other materials. All these additions allowed the ganch mortar to have properties the builder needed in a given locality. Sand and brick crumb were inert aggregates, while loess was used to retard the setting process and to add to the cementing properties of the mortar. Ash was added to improve the water-resisting properties of the mortar. Clay and charcoal were mixed with ganch to add plasticity to the bond. Mortars of different qualities are required for one and the same structure. This was well understood by the ancient architects. The ancient builders obtained mortars of the required properties by varying additions to the ganch. In the mauselcum of sultan Sandjar in the Old Merv (the 12th century), the bottom courses of brick are laid on ganch with ash and charcoal; the middle part courses - with brick powder, and the top courses - ganch with sand. The ancient craftsmen were being in constant searching for improving the mortar that seemed to be most perfect. Finally, they obtained "sheresh", a powder of dried and ground roots of plants, a small pinch of which per usual ganch batch of 10-12 kg made it resistant to water and essentially retarded the rate of setting. Most of buildings in Central Asia were erected with using the ganch mortar possessing improved elastoplastic properties, compared to the lime mortars.

The erection of these structures began with digging pits the bottom of which was covered to a depth of 60-80 cm with a dense mass of raw pottery clay with no admixtures. Such a plastic clay padding can be seen almost under all architectural monuments built from the 10th to the 17th centuries. Sometimes, the pit bottom was stamped before laying clay by the hoofs of horses. A foundation of burnt brick as a rule on a clay mortar was laid on the base prepared in this way. The foundation foot was slightly curved. This is the first improvement against earthquake shocks. The clay padding having plastic properties absorbed shocks caused by earthquake wave. The curved foundation better penetrates a plastic mass. To prevent the clay padding from drying, special measures were taken in the form of various fills and pavings. At present time various rubber-metal coursed antiearthquake shock-absorbers are used in place such elastoplastic paddings.

After the foundation of brick had been laid on clay the thick joint layers of which perform the function of elastic pads, a brick course was laid on a lean loess mortar containing up to 80 per cent of sand. The plinth wall of the building was then laid above. This layer of lean mortar under the whole of the building is a next seismic-stability improvement. A millennium later it would be called a sliding belt and would be made of two strips of stainless steel or plastic. The purpose of the sliding belts is to reduce the earthquake motions transmitted from the ground to the building. When an earthquake force overcomes the friction force of this belt, the structure slides, thus decreasing the earthquake load. The less the friction force, the better. By the way, sliding belts of sand are used now in China, and in Japan a lubricant is used between the belt strips, which essentially reduces the earthquake effects.

So, the plinth wall has been laid. Before setting up to erecting the walls, the top surface of the plinth wall is thoroughly levelled with a layer of mortar, then a cane belt over it is laid which is a uniform course of cane, 8-10 cm thick. The cane is thoroughly laid, straw by straw, square with the wall plane, so that the cane is not crushed by the bricks of the above wall laid on it. Sometimes, there were two such belts; sometimes, there was laid none. Their purpose is the same as that of sliding belts and elastic pads, i.e. to reduce motions transmitted from the base to the structure during an earthquake. My thought is to show you a present-day analogue of the cane belts. First I wished to name cast-iron balls providing 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 belt. The structure of the walls was such that they by themselves were a seismic-stability improvement. Clay may be used as a mortar for the walls.

The walls of the mausoleum of Fakhr-ad-din Razi, the 12th century, were laid on clay, and its dome was laid with use of ganch. The mausoleum is still surviving. However, most often the walls were laid on ganch. It is of interest, how the walls were being erected. At the wall foot the mortar joint thickness was equal to the brick thickness (5 cm). The mortar joint thickness decreased with height to be 10-12 mm at the top. The result was, that the ganch volume in the total wall volume was up to 30 per cent, which imparted elastoplastic properties to the wall, which is required by the seismic-stability requirements. The ganch was also used to lay all elements connecting the walls to the dome and the dome itself. These were earthquake proof improvements used by the Central Asia architects to make their buildings resistant to earthquake shocks [30]. It is time now to consider some characteristic structures of this region.

Again Ancient Craftsmen of Brickwork

If somebody of you will be happy to get to Central Asia and be given a chance to visit some ancient monuments, try to scrutinize the pattern of their brickwork and you will see the Eighth Wonder of the World. I am always astonished by the brick patterns weaved on the minarets raised into the heavens. A minaret is a tall tower tapering, with height with stairs leading up to one or more balconies from which the faithful are called to prayer. The taper surface of the minaret is decorated with repeated patterns laid of coloured brick. It seems that with height, these patterns will not align with violation of the pattern harmony. But this never happens, and ring after ring higher and higher you can see a complete pattern. To satisfy oneself that it is so, 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, the whole of an intricate structure is built of brick of one size. A mosque of the 11th century having an intricate configuration, known as Talkhatan-baba located near the town of Mary is fully built of brick of standard size 25 by 25 by 5 cm [31]. According to this work, the use of burnt brick was started in this region in the 13th century and its shape was dictated by the seismic stability problem to provide uniform and monolithic masonry. I would say still more, the brick layout in the masonry, brick patterns are dictated not only by aesthetics, but also by the properties a given section of the wall or dome is to be imparted. There exists a legend that the ancient craftsmen burnt a brick so that it rang when struck. More than that, it must produce the sixth note "la". I have such a brick with traces of the craftsman's hands at home, and it actually makes a ringing sound when struck.

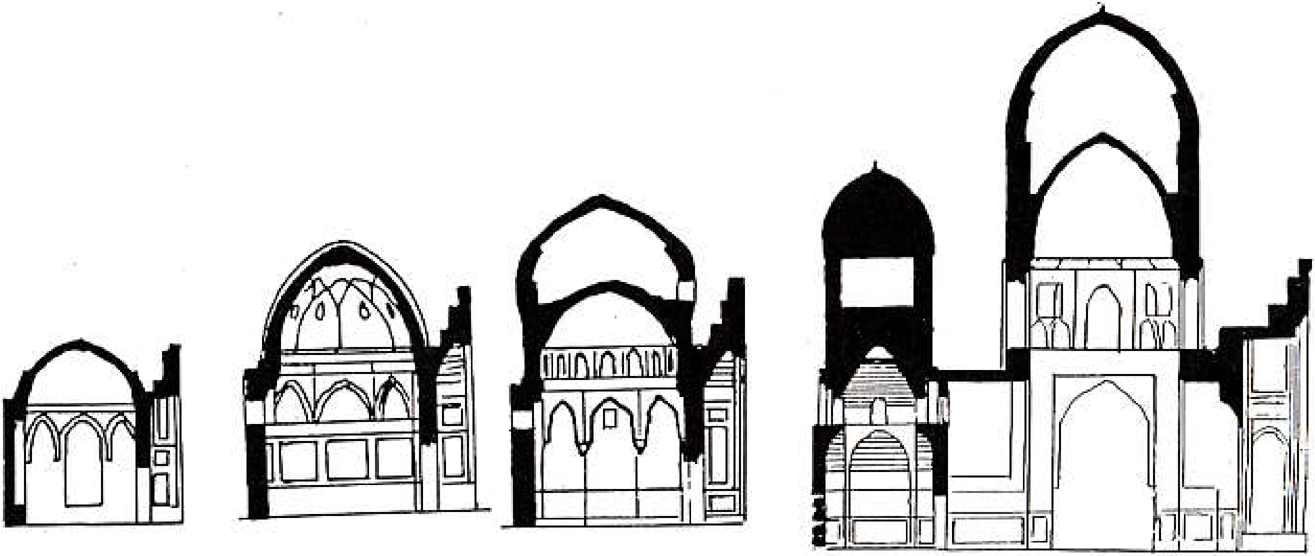

Fig. 63. Evolution of Dome Structures of Central Asia Mausoleums

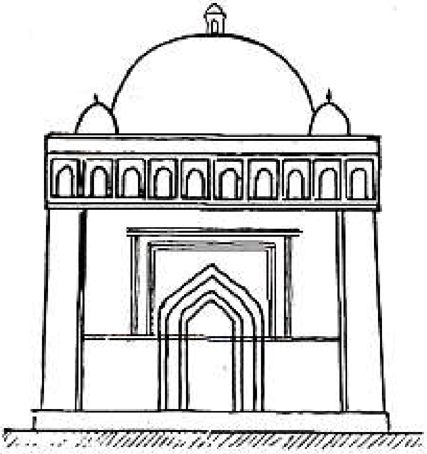

Fig. 64. Ideal Geometry of Mausoleum of Samanids

Let us start our trip to the country of brick and sun with the city of Samarkand, a city in Central Asia destroyed by Alexander the Great in 329 B.C. Samarkand later rose to fame as the centre of the silk trade, becoming the subject of much legend in West. It was destroyed again by Genghis Khan in 1221 but later became the capital of Tamerlane's empire. By 1700 it was almost deserted, but in 1868 it was taken by Russia and in 1924 was incorporated into the Uzbek Soviet Socialist Republic, briefly becoming its capital. The entire history of the construction art of that age can be seen in the ancient monuments of that city.

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 be probably enough to consider a complex of religious structures the formation of which was started in the south of Samarkand, the 11th century, near the imaginary grave of Kusam ibn Abbas (Shakh i Zind - alive King); its construction was completed in the 15th century. Kuzam ibn Abbas, a quite real and important person, was a cousin of Muhammad (570-632 A.C.) the founder of the Islamic faith and

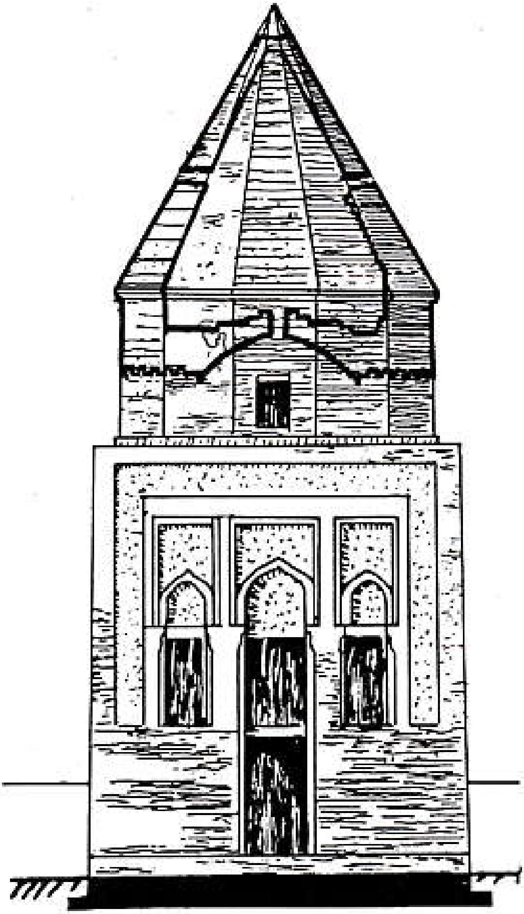

Fig. 65. Smoothness of Joints Between Geometrical Bodies of Fakhraddin Razi Mauzoleum

community. With the first troops of Arabs he came to Samarkand in the 7th century and was killed there.

Listen, if we return to the history of construction we are interested in, then analysing the architectural monuments of Shakh i Zind, we can see the evolution of architecture generally of the whole of Central Asia, of course, with some exceptions.

The evolution of dome structures is shown in Fig. 63 [32]. 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, a bit arrow-shaped. The dome thrust is taken up by the walls reinforced by the arches spanning the wall niches. From the standpoint of seismic stability, this mausoleum is O.K. The presence of the portal, however, affects the centricity of the monument. Note, the most early mausoleums were better from the standpoint of the structural-spatial and planning concepts, satisfying the principles of earthquake-resistive construction. A classical example in this respect is the mausoleum of Samanids in Bukhara, the end of the 9th century, whose composition is most simple [33]. It is a low-built cube, 10.8 by 10.8 m in plan, 9.0 m high (Fig. 64) erected on a small brick platform. Like the whole of the mausoleum, the walls, 1.8 m thick, are laid of ganch-bonded bricks. By means of arch-type trompes, the wall square is transferred into an octahedron which is smoothly jointed to a spherical dome [33]. Here you have an example of ideal proportions and dimensions required for an earthquake resistant building of rigid structure. This was prooved 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 [34]. As to me, I wish to call one more perfectly proportional mausoleum with no portal which has no analogue anywhere in Central Asia [35]. This is the mausoleum of Fakhraddin Razi in Kunya-Urgench, the 12th century (Fig. 65) which survived after Urgench was defeated by the Mongols. The mausoleum is standing on a foundation extending at the footing. The mausoleum 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 with height 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 dodecahedral drum smoothly transferred into the

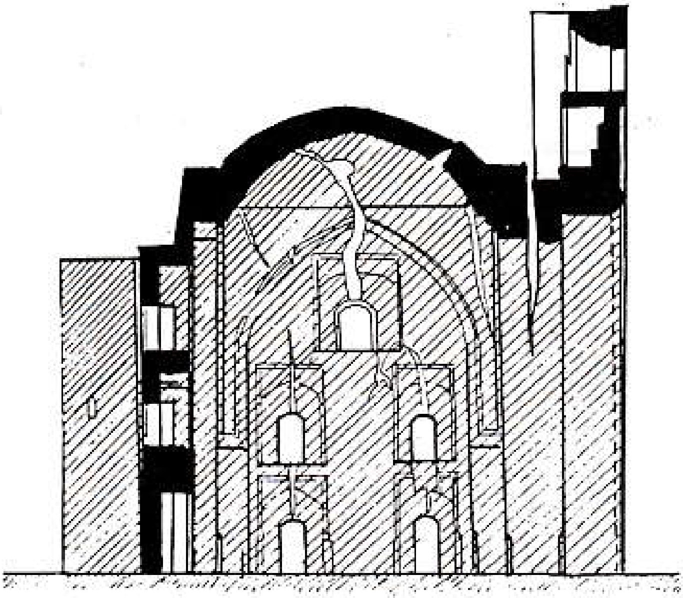

Fig. 66. Last But One Stage of Destruction of Mosque in Anau

walls. This drum houses a massive internal dome. The outline of this dome is also shown in the figure. The external and internal domes together with the drum form a single closed contour which corresponds to one of the principles of earthquake-resistive construction. The walls of this mausoleum are laid on clay mortar, while the dome masonry is ganch bonded. The result is that the rigid shell of the domes rests on a massive elastoplastic body which serves as an insulator from ground shaking caused by earthquake waves. The structural diagram in question is very like what we saw in studying the temple of Garni.

After the short excursion into depths of ages, we shall return to Fig. 63 showing the evolution of domed mausoleums. This evolution having started with ancient centrical mausoleum, then went over from equally important facades to separating a major facade and decorating it with a splendid, frequently very massive portal. The portal-dome structures appeared which thus were not centrical with equal distribution of weights and rigidity, which is dictated by the principles of earthquake-resistive construction. This generation of mausoleums appears in Fig. 63 under No. 2. This is 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 pressures exerted on the ground under the foundation and under the portal are different. The pressure under the portal is generally greater. This was known to the 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 weights 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 accordingly the destruction of the entire 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. 66). The mausoleum situated on a low hill near the city of Ashkhabad is built of rectangular burnt brick of very good quality with the use of ganch mortar [36]. This did no good, the destruction of this monument started with separation of the portal and cracks in the dome and ended with complete collapse during the Ashkhabad earthquake in 1948.

The next stage of the evolution of the domed structures is represented by the mausoleum of Shirin-bek-aka, whose sectional view is shown in Fig. 63 under No. 3. In this case, use is made of a double dome, an external and an internal domes, the external dome being of thrustless type. Whether you like it or not, a question arises why the shape of Mohammedan domes is such. Whether it is associated with religion, or a choice is made of a perfect structural concept. I think both apply. Figure 67 shows the sectional view of a dome in India [13] from which it can be seen that it is as if a balanced system. In this case, at least at the centre of the dome, each stone is laid so that its inward overlap is balanced by its outside thickening. The efficiency of the Roman buildings has already been discussed, but we may say the following that applies to

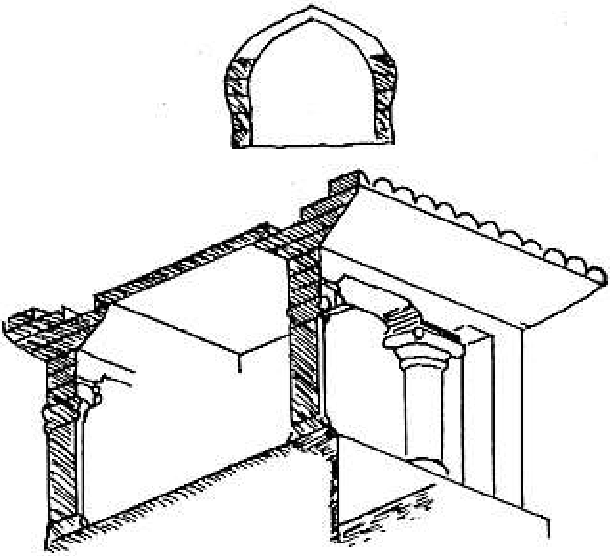

Fig. 67. Selfbalanced System of Dome

the whole of the ancient architecture. The ancient builder did his best to erect strong, reliable and cost-saving buildings meeting the architectural requirements and standing for ages, and he could not do otherwise. Recall the lancet Mohammedan arches. They are beautiful from the artistic point of view and reliable from the structural point of view. 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. 68). The double domes shown in Fig. 63 form a closed uniform contour which is good from the standpoint of seismic stability.

In the late 14th and early 15th century new essential changes occurred in the architecture of religious and memorial structures. This is associated with the appearance of the world empire of Timur with the capital in Samarkand, where immense riches were concentrated, the best craftsmen arrived from all lands of the empire, and wherein huge armies of unskilled labourers were formed. All this created pre-conditions under which the evolution of the domed structure 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 the structures grew larger, the architects became ill with giganto-mania, the towers of minarets became erected higher and higher. The complex problems of building huge structures called for the adequate development of the construction technology. Increasing the sizes of mausoleums, erection of very high slender minarets, large spans of domes raised very highly, all this contradicted with the principles of earthquake-resistive construction. The ancient architects were well aware of that and started their fighting for seismic stability of their gigantic structures. The depth of foundations was essentially increased. Normally, foundations were laid at a depth of 4-5 metres 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 brick on ganch satisfied the new more severe requirements. It is monolithic, strong and ductile. The most difficult problems arise with an increase in the span of vaults and domes. All domes were made double shell for uniform distribution of the load caused by a large span dome. A special system of brick ribs was made which transmits the load to the walls and the inner dome. The most important was that a system of girth arches supporting the vault and dome drum had been created. The system allows creation of large internal halls without essentially increasing the dome diameter. The weight of the entire structure was reduced by using this system. Note, that the girth arches of Central Asia resemble the double intersecting arches of Armenia which also support vaults, but this system being much more complicated. There was perceptible tendency of materially reducing the weight of the structure; the heavy vaults and domes made of brick before, now are made as thin-walled structures of ganch [33].

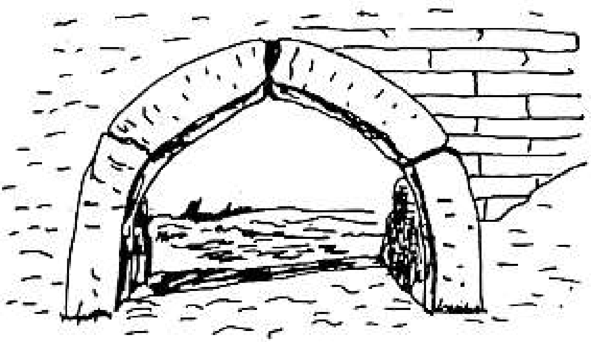

Fig. 68. Seismic Stability of Lancet Arch

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. 63 gives an example of a double-dome mausoleum built in the 15th century ascribed before to Kazy-zade Rumi. Referring to the diagram, this mausoleum does not satisfy the principle of uniform distribution of weights and rigidity at all. 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 as this, the seismic stability of a structure can be ensured by the corresponding structural improvements. This mausoleum is surviving until now [32].

It follows from the above that the ancient builders were well aware of the danger from the standpoint of seismic stability, represented by the giganto-mania in the architecture. Growth of structure dimensions, raising the centre of gravity of the entire structure due to raising the domes, increasing the spans of arches and domes, plus the asymmetry of the multidome mausoleums, all this breaks the principles of seismic stability and affects the earthquake resistance of the new generation against earthguakes.

Let us consider one more mausoleum of that time.

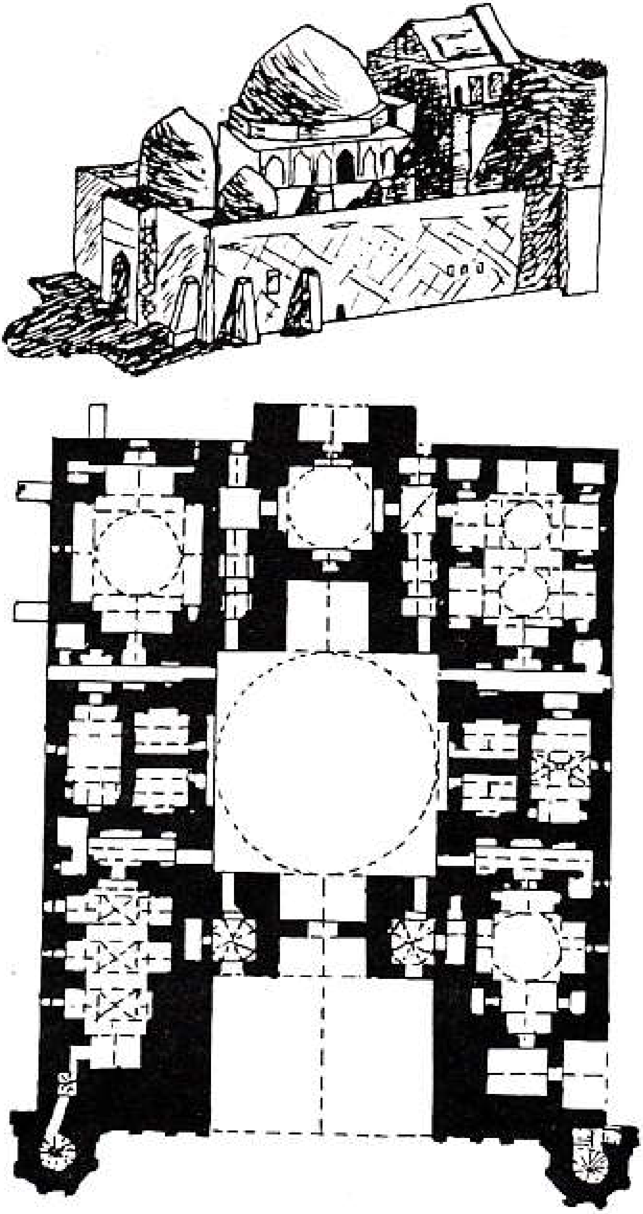

Fig 69 Seismic Stability of Lancet Arch

After his brilliant victories over Golden Horde, Timur being guided by political and religious motives bade his architects to erect a new burial vault of unprecedented magnificence and size in the city of Yasy, now Turkistan, in place of the old burial vault of sheikh Akhmed Yasavi. Timur himself directly participated in the discussion of the dimensions of the structure and its configuration. The construction was started in 1397 and was conducted at a very rapid pace, but in 1505 Timur started a campaign against China and suddenly died. This stopped the construction [37]. The construction 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 in which food was distributed among pilgrims twice a week, and so on. The mausoleum-mosque is an enormous portal-domed building with one plane of symmetry. The general view and plan of this structure is shown in Fig. 69. Its dimensions in plan are 46.5 by 65.5 m, its portal is 50 m wide, the span of the portal arch is 18.2 m, the diameter of the largest brick dome of those that 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 3.0 m. The seismic stability of this outstanding monument of architecture is as follows.

The mystery of this structure starts with its foundation. It remains an enigma why the gifted builders of that splendid structure treated its foundation in a light-minded manner. Usually, the foundations built at the time of Timur show excessive strength and weight. They were laid of large stones on a lime mortar with ash which made them waterproof and strong. Under the mausoleum building in question, however, there is no solid foundation. A few courses of brick careless masonry were laid under its walls, only at a depth of 25-30 cm, the pit under the heavy portal was filled with large pebble and soil [38]. The cause of erecting the ensemble of Akhmed Yasavi on weak foundations is, to my mind, very simple, and can be understood. 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 best to satisfy their sovereign 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 builders did careless foundation work, owing to circumstances outside their control. Fortunately, severe earthquakes do not yet disturb seriously this monument. However, the poor foundation is the major cause of its destruction due to unequal settlements. Much injury was done to the base of the mausoleum in 1846 by the Kokand troops who in order to captivate the ruler of Turkistan, Kanat-shah who ensconced himself in the mausoleum, used a system of dams to flood it and the mausoleum remained flooded for a long period of time.

However, the major secret improvement that saves the mausoleum of Akhmed Yasavi standing on poor foundations under conditions of increased seismicity and severe moistening of loess settling grounds consists in that the mausoleum is splitted into eight independent spatial blocks. Structurally, the antiearthquake joints are in the form of four through two-storey corridors (Fig. 69) which allow individual 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. Such sectioning into separate blocks was used by the ancient architects to overcome the giganto-mania.

Though sheikhs always lived around the mausoleum-mosque, supervised it and performed rituals, its construction remains uncompleted till now. For example, the main portal has not yet two minarets proposed by Timur. Neither it has facing. Admittedly, the ruler of Bukhara, Abdulla-khan, tried to complete the construction of the mausoleum by the end of the 16th century. At his time, the main arch of the portal was fully spanned and something more was done [37]. It's a pity, he did not order to erect the minarets which ought to add load to the portal thus helping it take up the thrust caused by the main arch.

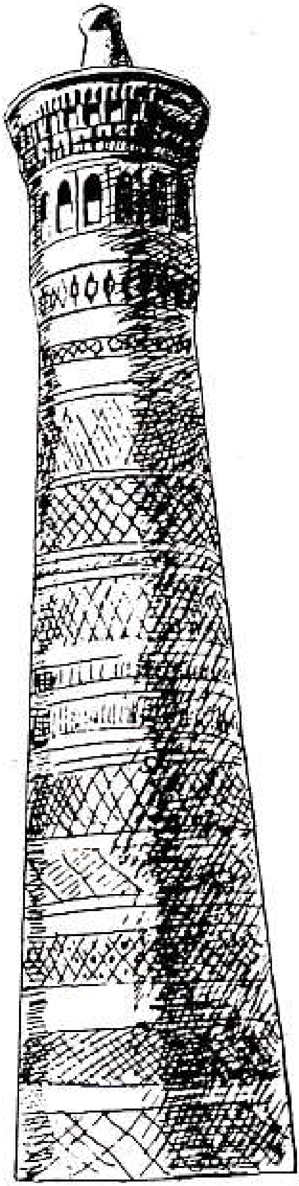

Fig. 70. Minaret of Kalyan

We have talked about the mausoleum of Akhmed Yasavi to tell the reader about sectioning large buildings into separate blocks, which was known to the ancient architects. I wish to mention one more fact of interest in concern with this monumental structure, i.e. an arch of burnt brick laid on an unknown tarry mortar with very high ductile properties. This mortar was a mixture of an unknown tar with sand and loess. Being applied to the brick in a hot state, it forms a very strong bond, imparting high strength and improved elastoplastic properties to the masonry. It is clear that solely such a mortar, if used in wall masonry and in such important structures as arches and domes, makes them exclusively durable and resistant to earthquake shocks [30]. This simple interesting example makes me draw a wide conclusion on the art of the ancient architects. I'll try to do it as follows.

The creative work of the ancient architects consisted of three stages: first of all, a clearly set task; secondly, good knowledge of traditions, and in the third place, searching for something new in order to carry out the work better than it is possible in accordance with the traditions. As a result, a new unknown tarry mortar was devised. Dear reader, if you are concerned with the earthquake-resistive construction, you must confess that you were not aware of the anticarthquake improvements of the ancient architects, until you have encountered this publication. As you have seen above, there are much interesting and wise in the experience of the ancient builders that you must know. There is one more example in this respect.

The minaret of Kalyan towers over the city of Bukhara. It 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 blue sky. Seeing them, one can hardly believe that they are laid of brittle brick. More than that, frequently they stand alone, without a mosque attached to them. Their mosques, more rigid and solid, and more strong as it might seem, have been destroyed by earthquakes long ago, while these very slender structures of brittle brick featuring flexibility are surviving. Twice minarets were erected at the cathedral mosque in the city of Bukhara and each time they collapsed. Finally, the third attempt was a success. In 1127-1129 the minaret of Kalyan (Fig. 70) was erected on a very strong and deep foundation laid at a depth of 10 m according to one source [33], and according to another work [34], the pit of 13 m in depth did not reach the rock base. The minaret was laid of burnt brick ganch-bonded. Its present height is 46 metres. There is a supposition that another turret stood above the lantern topping the minaret which collapsed during an earthquake. The minaret diameter near the octahedral high socle is 90 metres. The intricate roofing above the lantern is supported by 16 lancet arches forming the same number of openings through which at past times sixteen muezzins simultaneously called at the hours of prayers. As it looks today, the minaret of Kalyan cannot be called very slender, its taper shape rapidly narrowing with height looks like low-built. The natural selection has shown that the minaret of Kalyan is earthquake resistant. It survives, while many other minarets collapsed. Only a few have survived. It is just these few servived architectural monuments we are interested in. They give information about the depth of foundations, configuration of earthquake-resistive buildings required in an earthquake dangerous region, and finally about their dynamic characteristics which are desired for buildings being built in a given earthquake dangerous zone. In addition, old scars on their walls inform us about bygone earthquakes.

One more problem important from the standpoint of earthquake resistance we must dwell upon consists in the joints between the walls and domes. As a rule, this problem was splendidly 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 used in Central Asia was as follows. Arched trompes were used to span the square corners. These trompes supported an octahedron on which then was conjugated with the dome. Such a conjugation is shown in Fig. 71; an example is one of the mausoleums built in the 11th century [33]. You see how the walls are lightened by niches spanned by lancet arches. Laid in the piers between the arches are ribs

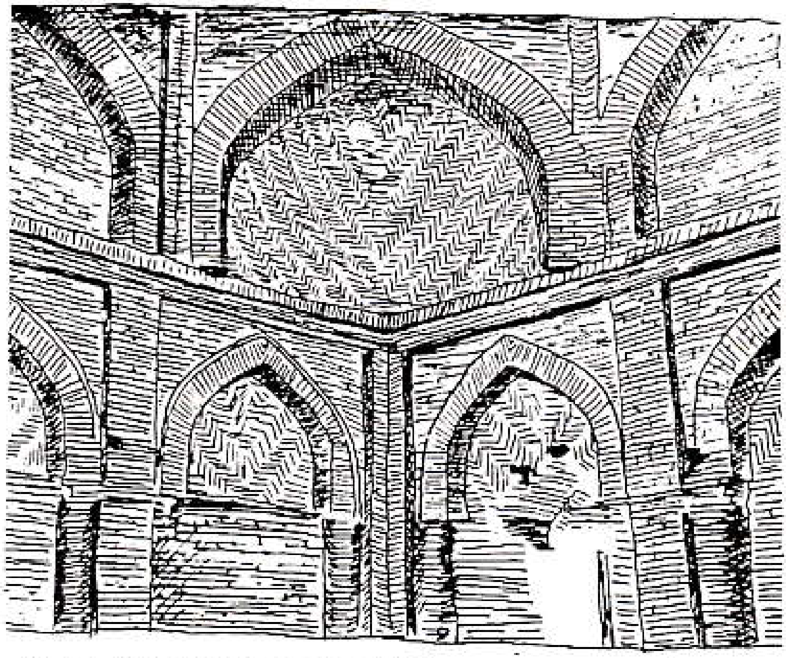

Fig. 71. Conjugation of Square and Polygon

of rigidity in the form of columns embedded in the wall. A system of the arches forming the octahedron is located above. Next, the dome is laid which was improved, lightened, and reinforced during ages.

One more point of interest is as follows. Note, what a wide use of curvilinear structures, such as arches, vaults, domes, was made by the ancient architects. All these structures, built well, demonstrated their durability and reliability, and at the same time served as decorations of monumental structures. Now note how rarely these structures are used at present time, everything being simplified as far as possible. This depletes our architecture in particular, and our life in general.

What a Column!

While studying our problem in Central Asia, we never mentioned columns. Why so? Let us look into

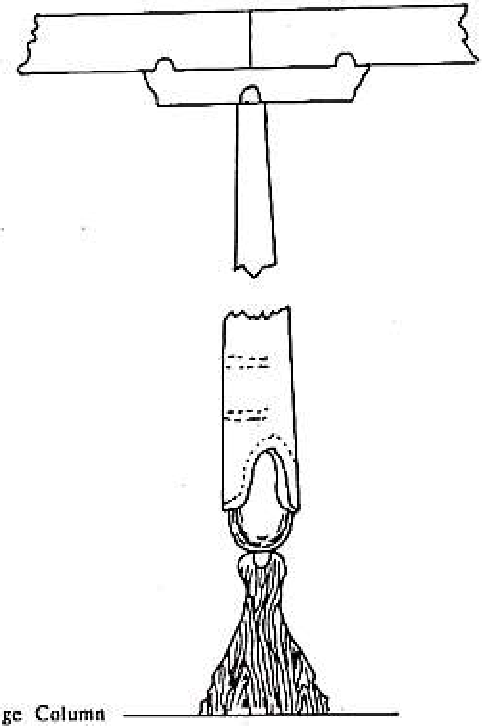

Fig. 72. Multihinge Column

this. No stone columns remained in the structures that have survived, although we know that there were attempts to use them. About 400 columns of marble, more than 4 metres high, were used in the cathedral mosque of Timur, Bibi-Khanym by name, its dimensions being 83 by 62 metres. This mosque had a misfortune. It collapsed during an earthquake. There were evidently other examples of misusing stone columns. The ancient architects, however, did not repose their trust in such columns.

With taking into account the earthquake danger of the region, the stone columns could not be imparted enough flexibility, as was required according to their principles. Brick pillars did find their application as intermediate supports, since they could be made flexible by means of the known mortar methods. The brick pillars were of considerable diameters, up to 80 cm, the masonry being made with use of thick courses of ganch mortar. They were in particular widely used early in the 11th century. Later on, these pillars were discarded [30].

Instead, widely used in Central Asia were and still used light wooden columns, being structurally very perfect (Fig. 72). Referring to the figure, it is made as follows. First of all, it has a beautiful fretted base widening towards its foot. The top of the base has a socket to receive the lower tenon of a 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 at its ends which fit seats made in the ceiling beams. The result is as folows. The column is hinged at both its ends. Therefore, it works merely in compression with no bending, thus being loaded uniformly. Next, the use of the bolster reduces the column-to-column span, and thus materially reduces the maximum bending momentum of the load-bearing beams. More than that, the use of tenons prevents the whole of the assembly from coming loose and its elements from misfitting each other under heavy shaking occurring during an earthquake. Finally, the most important is the fact, that the double-hinged columns will convey no motions caused by earthquake shocks to the ceiling from the ground base. The ceiling will receive horizontal motions only from the walls which 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 spreaded traditional open terraces, ayvans. The same column was used in the monumental building. The famous Juma-mosque in the city of Khiva 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 city during the divine services on Fridays. The flat ceiling of the Juma-mosque is supported by 212 columns of the above-mentioned structure, four of which are ancient, and feature carving of particular beauty. These columns refer to the 10th-11th centuries [39]. As you see, the

Juma-mosque has proved the seismic stability of its structure by its thousand-year existence. The structure is as simple as a masterpiece of genius can be. It has no rigid units at all: a light flexible ceiling, all joints have hinges, the low horizontal loads are conveyed to the walls located along the perimeter.

In talking about the Central Asia structures with wooden columns, I recalled another structure, very alike in the idea which existed at the same time far away in Japan. The high seismicity of the lands in that country was taken into consideration and everything was built of wood, up to the 16th-17th centuries, as it was well understood that the wood is an ideal material for earthquake-resistive structures, since it is light, elastic and strong. In Japan, the following structure existed in the housing construction [22]. Large stones serving as the base for thin wooden columns were placed on a level course of gravel. The top of the stone had drilled sockets into which wooden posts were inserted to form the skeleton of the entire building. These posts carried a light roof and light walls of wood and paper were made between them. Certainly, the structure was fairly resistant to earthquakes. Each stone base moved in its own manner dictated by the ground motion caused by an earthquake. At the worst, some damage was caused to the flexible connections between the posts.

Since we are talking about the earthquake resistance of wooden structures, let us consider this problem in more detail. To this end, we'll proceed to the wood kingdom.

IN WOOD KINGDOM

Russian Izba and Japanese Pagoda

Strange as it may be, but that is a fact. Many competitions are conducted in the world. There are contests for the miss beauty, the most stupid story, but there was no competition for a structure most resistant to earthquake. Though, to my mind, it would be as interesting a competition as, say, competition for who swallows more iron items. I think, it will show as follows. Certainly, such a competition must be conducted in Japan known for total computerization and thousand-ton seismic test platforms capable of recording any earthquake. A choice might be made, for example, of three reference, natural, man-made multicomponent records of earthquake: one with a great horizontal component, one with severe twisting, and the third one producing a severe vertical shock. Then, using these three records, all structures or their models made to a certain scale sent for the competition from all lands of the world, are to be tested for seismic stability. This, as usually, must be accompanied by assigning prizes and betting. Like the case is with medicine, everybody is interested in the seismic stability, and the competition is demonstrated by the TV all over the world. Everybody can see the behaviour of the earthquake-resistant structures of the past, present, and future under the earthquake conditions. Such structures, for sure, will take part in the competition. You'll see intricate spatial deformation of the buildings, break failure of the structures at points of overstress, and subsequent avalanche collapse of the entire building. It will be possible to compare the behaviour of different structure designs and select the best one. No such a competition has been yet conducted, and persons who are interested in the problem either due to love of knowledge, or because of practical needs, often try to get at the truth in a speculative way, going over the structures you know in your mind. Since I have put the question, I must give the reply to it. Believe it, or not, I am sure that the prize will be won by a conventional Russian izba with minute improvements. As to the traditional structures, the second place will be taken by the Japanese pagoda (Fig. 73). Let it be discussed in more detail.

Recall the structure of a conventional Russian izba whose evolution covers several centuries. The people were seeing to it that the izba was mainly durable and heat insulated, without paying attention to its seismic stability. Though, after the Russians have pioneered Siberia and Far East, the Russian izba found itself in the Transbaikal region, Altai area, Kazakhstan, regions of increased seismic stability, wherein it best stood to earthquake shocks. And this is due to its good quality. Each Russian izba is built on the basis of the so-called log framework. So an izba is a house built of logs which are horizontally laid and notched and fitted at the ends to prevent spreading. As a result, each log laid in the framework becomes coupled up with the log under it and with the cross walls to form a single, nondetachable system out of which none of the logs can be knocked out without destroying the whole of the wall. This framework is free to deform in any direction due to shifting the logs relative to each other along the notch. This system naturally provides good damping, its material being light, strong, and ductile. The structure features the symmetry property. The fact that the Russian izbas (log houses) feature high resistance to earthquake shocks has been proved by many earthquakes. During the Irkutsk earthquake, November 7, 1958, magnitude 8-9, the log houses suffered less of

Fig. 73. What is Most Resistant to Earthguakes?

all; the damage was in the form of fissures that occurred in the corners of some log houses. During the Vernen earthquake, 1910, whose magnitude was above 9, the log houses with a good stone foundation under

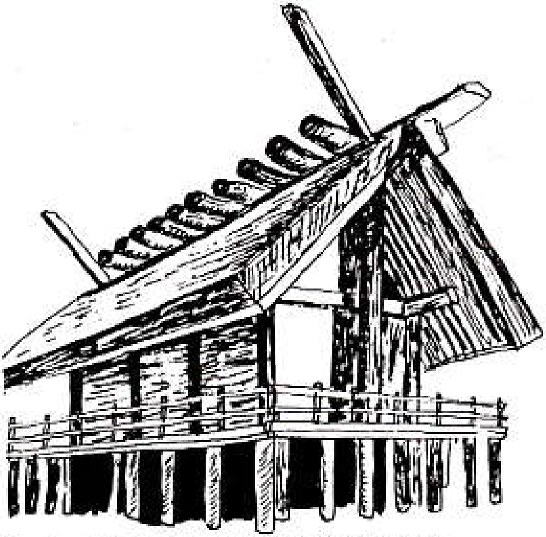

Fig. 74. Structural Perfection of Shrine Named Soden

the whole of the house did not suffer at all [40]. We'll still return to this earthquake. So, what should be improved in the Russian izba, so that it could participate in the competition of the structures most resistant to earthquake with pretensions to winning it? The reply is as follows. The log house must be given vertical ties to prevent the logs from being knocked out of the notches, and the horizontal rows of logs (venetses) from slipping off each other, even at very intensive shocks. For example, metallic rods may be threaded through the entire framework from top to bottom at the corners and secured above and below. This improvement is not an invention devised by me. A structure in which the wood was reinforced by metal to improve its resistance to earthquake shocks was offered at the beginning of our century. Where and what for, you'll know in the next section. Now, some talk about the Japanese pagoda.

In the deep past, in Japan, a beautiful custom was introduced to restructure the temple complexes of wood every 20 years. In that, a duplicate was built with copying minute details. This time interval was not always followed. Nevertheless, exact duplicates were built, and that custom allows us to study the structure of certain most ancient architectural monuments in good conditions at present time. Let us consider one of the most ancient monuments of the wooden architecture of Japan which was only wooden till the 17th century. This is a rectangular (in plan) shrine named Soden (Fig. 74) included in the temple complex Ise-nayku devoted to the Sun goddess - Amaterasu-omikomi, the 3rd century A.D. [22]. It is this most ancient structure that well shows the principal structural difference of the Japanese wooden structures from the Russian izba. The Japanese structures were based on poles one end of which was vertically dug in the ground. The remainder of the structure was threaded on these poles. With the Russian izba (log house) all is turned through 90 , the logs are laid horizontally and have horizontal and vertical ties between one another. The ties feature high ductility. The logs can slide along the notches, relative to one another with an increased coefficient of damping. The only disadvantage is that the horizontal rows of logs have vertical ties which do not work in tension. So, 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 vertical fastening.

So, in the Soden shrine the vertical pole-columns are connected by transverse and longitudinal links into a single spatial skeleton. Everything is done in compliance with the principles of earthquake-resistive construction. More than that, 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 which is coupled with the spatial skeleton of the entire structure, thus supporting it and making it more resistant to earthquakes. The frame and the skeleton, probably, differ in rigidity, the frame being more rigid. Such combination of elements having different rigidity into a single structural system is characteristic of the earthquake-resistive construction of ancient Japan. There will be given later an example of an earthquake-resistant structure comprising two systems of different rigidity. This was not yet encountered by us. Note one more typical element of seismic stability used by the Soden shrine which was also employed 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 connected to the skeleton. These poles perform the functions of seismic insulators. At the ground level the poles are not coupled with each other, and thus can move regardless of each other in compliance with the intricate chaotic motions of the ground during an earthquake. Besides, the poles feature some flexibility and somewhat damp shocks caused by earthquakes. At the shrine floor there is a common linkage including a round-about terrace in which 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 super-reliable Japaneses who made the joints between the structure elements will not be discussed here. As you see, all the principles of earthquake-resistive construction are met by this structure.

There is one more example of a wooden structure raised on poles. By its horizontally laid logs it resembles a Russian izba, except 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 treasury of Cesoin situated in the ancient capital of Japan, Nara, built by emperor Cemu in 752 (Fig. 75). The rectangular (in plan) building rests on 40 wooden columns, 2.7 metres 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 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 [22]. During an earthquake, the work of this structure is ideally simple. The supporting columns dug in the ground

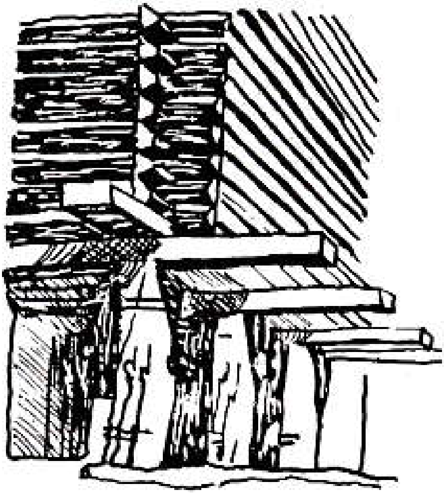

Fig. 75. This Temple Has No Seismic-Stability Problems

move independently. The crosswise system of beams connecting the columns' top ends, and the building itself are so flexible and ductile that they can move and breathe without overstressing and destruction, like the tops of the relatively flexible columns move and breathe.

There is another still more original 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 entire structures and their parts characteristic of the Chinese architecture, as well as the general composition of temple complexes [22]. From this time wide applications in Japan were found by wooden pagodas in the form of tower structures, up to 30 and even to 50 metres. All those pagodas were built, following one and the same principle that was being shaped during centuries (Fig. 76). The whole of the structural system is composed of a few square (in plan) storeys of diminishing (with height) size which form a skeleton with corbeled cornices. The storeys have a pent roof. The result is as if a multistorey structure, but use is made solely of the first storey space, the other storeys being used for emphasizing the significance of the pagoda as a whole. Storeys are made so that the perimeter poles support a closed belt consisting of a few courses of logs laid horizontally like in the Russian izba. These belts form the base for the poles of the next storey, and so on up to the top. These logs horizontally laid at the level of each storey are nothing more from the present-day point of view than a seismic stability belt used to provide a horizontal bracing of the storey elements. From this standpoint, the Russian izba is a single antiearthquake belt.

It is good that the pagoda diminishes in size with height, but not good that its structure has its vertical posts break at each storey. There is one more essential disadvantage in the pagoda structure, as the seismic stability is concerned. This is an excessive weight of the entire structure due to a heavy roof of clay tiles. All these shortcomings are compensated for by the fact that the pagoda is a structural system consisting of two subsystems of different rigidity. The above-described structure of storeys with a heavy roof is a fairly flexible system. Its centre is pierced by a still more flexible system in the form of a pole made up of a gigantic tree trunk, or of 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 as the case is with the Central Asia columns. The outside skeleton and the internal flexible pole are connected to each other at the levels of two storeys. The whole of the pagoda is supported by a stone base. One of the factors providing the exclusive seismic stability and their ability to stand to typhoons of these pagodas consists in that it comprises two systems of different rigidity. Being dynamic in action and each having its prevailing period of oscillations, earthquakes and typhoons affect one of the subsystems, either the flexible or more rigid one, depending upon their period of oscillations. In this case, the other subsystem, as if opposite, will shake less and serve as the damper of the oscillations suffered by the former subsystem. With the structures of this double system, it is good practice to have the periods of natural oscillations suffered by the flexible and less flexible parts essentially different. Maybe from this point of view, the ancient builders were wise making a heavy roof of the skeleton system of the pagoda to essentially increase the period of its natural oscillations, and securing 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 the pagodas has been proved by their multicentury history, and I was wrong saying that the heavy roof of pagodas contradicts the principles of earthquake-resistive construction. I judged it in a standard way, while the ancient builders approached the problem in a creative way. An example is a pagoda of the temple ensemble of Yakusidzi (Fig. 76), 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 metres [22].

The monastery architectural complexes included also temple buildings. These buildings also were built of wood on a stone base. As a rule, these temples were single- and two-storey as complicated in the structure as the pagodas are less the central flexible pole, but with the same bracing in the form of horizontally laid logs at the storey levels. With the structure of these temples, we are interested in that their timber beams 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 is 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, being disturbed by an earthquake, the whole of this hinged-

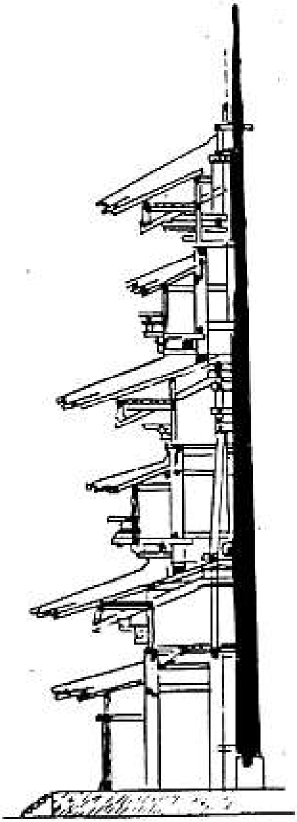

Fig. 76. Cross-Section of Pagoda with Flexible Core

join skeleton system 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 monastery Khoryudzi in Nara, the construction of which was completed in 607. The elements of earthquake protection are as before represented by a rectangular netting of free-standing poles which raise the building itself above the ground in a manner shown in Fig. 74. An example is the above-mentioned treasury Cesoin in Nara. Like the

Russian izba, it is built of horizontally laid logs, the entire structure being raised above the ground fairly highly (the 8th century). At that time, there was constructed an immense wooden building known as Daybutsuden, the hall of Great Buddha, related to the architectural monuments of the Nara period. Its dimensions (in plan) are 87 by 50 metres. It is 49 metres high; there are two pagodas, 97 metres high. The hall of Great Buddha has survived. Its two roofs were highly raised above the ground by a skeleton system, the lower part of which is formed by separate wooden columns which perform the functions of seismic insulators. A solid stone platform serves as the base for the whole of structure. The work of such a platform under the earthquake conditions has been discussed before. Let us proceed to studying almost as large a wooden structure as the hall of Great Buddha, also on a stone platform, but in this case situated in Russia and built more than 1000 years later. As to the seismic stability, the Japanese pagoda is a serious rival of our Russian izba.

A Bit Detective Story

Everything you will know from this book has resulted from a few years of my pleasant work of studying the history of construction and collecting information about the structural improvements used in the earthquake-resistive construction by the ancient architects. In a word, the result of my just another hobby. The needed facts were derived from diverse sources: new and old books on the history of architecture; some facts have been puzzled out when visiting the monuments of the past, some facts have been related to me by interesting people. Lots of facts have been accumulated, enough to write a very thick volume, but the book you are reading includes solely the facts associated with its logic. By way of an example, I'll tell you how I was investigating one, not so old, interesting, but little studied structure resistant to earthquakes which will be soon only one hundred years old. At the same time, I'll as if continue the story of the Russian izba.

It somehow happened so that the Sofia cathedral church in the city of Vernyi, now Alma-Ata, dear to me at present, slipped my mind. It was built by Russian military engineer A.P. Zenkov in a short period of time. It was founded in 1904 and hallowed already in 1907. I got to know this cathedral church from the book "Custodian of Antiquities" of Yu. Dombrovskiy [41] who is now widely published. In this work of art Yu. Dombrovskiy described in detail his arrival at Alma-Ata in the thirties, his meeting with the cathedral church and his talk with the watchman of this cathedral church, an old kazakh, who told him about famous Russian military engineer A.P. Zenkov who built this cathedral and reconstructed the city of Vernyi after a most severe earthquake of 1887. The talkative watchman related to Yu. Dombrovskiy a legend saying that the cathedral church was built without a nail from Tien Shan white spruce. In his book Yu. Dombrovskiy describes the cathedral church and the remarkable wooden buildings erected by Zenkov. In addition, he informs about their resistance to earthquakes. To the point, Yu. Dombrovskiy did not believe the watchman's legend saying that the cathedral had been erected without a nail, and he was right.

Naturally, from the standpoint of my hobby, I was very interested in all this and wished to examine everything to study the actual structure of the cathedral. In this event, I was a bit lucky and a very obliging man supplied me with the measuring drawings of the cathedral prepared in the course of its restoration with all section views and dimensions shown, except the indication of the internal metallic fasteners and design of the foundations. Before the further investigations of this structure, there is some information on the earthquakes involved [42].

The first severe earthquake in the city of Vernyi occurred in 1887. In addition to some preliminary minute shocks that made the citizens move outdoors, two more heavy shocks took place at an interval of 10 minutes. Most damage was caused to the buildings of different masonry, in particular, those of adobe brick, a brick church collapsed. In short, 1800 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 from that data that the wooden buildings are more resistant to earthquakes than brick buildings. Published in 1889 were "Measures Specified by the Technico-Construction Committee To be Applied in Urban Settlements of the Semirechensk Region" which recommended to erect as a rule wooden buildings on stone foundations with a basement under the whole of the structure and reinforcement of the corners by vertical beams. Recall the vertical studs to be fitted in the corners of the Russian izba to make it most resistant to earthquakes. After that earthquake the city was reconstructed in the wooden version.

The next earthquake occurred in 1910 and was still more severe. The ground displacement in Pulkovo near Petersburg was up to 4 mm. During that earthquake, none of the wooden structures were destroyed including our huge cathedral church built by that time. Again, only the brick stoves were destroyed. People and cattle were killed only in mountains, on pastures, due to landslides. The city withstood it. As we have learned to understand now, everything in such cases is dependent upon the system. There are many skilled builders in Armenia with her traditionally earthquake-resistive construction, but the towns of Leninakan and Spitak turned into ruins in 1988.

Next time I was lucky with the cathedral church, when I was invited to go to the city of Alma-Ata to tell the resultant story of the Armenian earthquake. Upon the arrival at Alma-Ata, I quickly settled my affairs and went to see the cathedral church. After entering the park, I saw the contours of the cathedral church known from photographs that came into sight behind trees. I was facing a bright, showing the colours of rainbow, particoloured many-headed structure in a pseudo-Russian style that just was in the fashion at the end of the past century when the design of the cathedral church was finished. I entered the church. A vast internal space opened up before me. It was brightly lighted through the wide windows of the underdome drums. From the floor I saw unlikely narrow piers between these windows. A thought struck me that the piers were not strong enough to support

Fig. 77 Multidome Wooden Cathedral Church

the dome mass during an earthquake. To satisfy my curiosity, an employee exactly retold me the story related to Yu. Dombrovskyi by the old kazakh. She said that the church had been built without a single nail and that it stood on a concrete slab and a sand padding. However, she did not go on with the story that during the earthquake of 1910, a fissure was formed on the ground surface, and that this fissure ran directly towards the temple, but took fright at the holy site, went around it, and took another way. All these stories were inventions and only proved the fact that the cathedral church had a good strong foundation. In any case, that woman (a guide) helped me in gaining information about A.P. Zenkov. In addition to some verbal information I was rewarded for my persistent searches with a tiny brochure illegibly printed on yellow paper [43] which contained some data I was interested in. And now about the structure of the cathedral church; I'll relate to you what I have found out and what we may guess.

As to the height of the cathedral church, there are

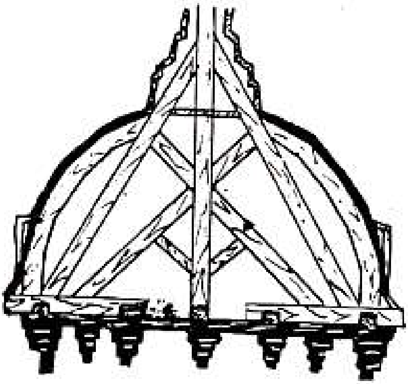

Fig. 78. Thrustless Dome of Cathedral Church

different versions. According to some publications it is 56 m and 54 m [42], 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 of the main dome is 39.63 metres. That of the cross on the bell-tower is 44.2 metres. The top of the base stone slab is 0.55 metre. As you see, it is far from 50 metres. However, with a wooden structure the height of 40 metres is fairly great (Fig. 77).

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 of the order of 13.0 m. That of the four small corner domes is of the order of 6.5 m. There is a rectangular 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, and the closed skeletons of the building, roof rafters, all these are made of the Tien Shan white spruce. Now let us have some talk about the structure of individual elements of the cathedral church.

Practically, the light spheric wooden domes with an internal skeleton are made thrustless (Fig. 78), since their total thrust is taken up by the flat coffer-type ceiling 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 connects through the window tiers to the roof. I was not lucky to 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 built by the same builder.

The base of the bell tower is in the form of a framework made up of horizontal timber sets, exactly as in Russian izbas. The resultant framework was fairly high, and since during an earthquake the high bell-tower will undergo bending moments, and thus tension stresses, the framework poorly standing 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 has done. He implemented 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 run through the entire height of the bell tower in the corners and tiers. This is the second kind of the vertical ties. All this seems to be a usual matter, but use has been made herein of the third, perhaps the main kind of vertical ties. The whole of the log framework had been threaded by eight vertical studs [43]. The studs involve the entire log framework of the bell tower, the high pyramidal roof inclusive and tie them to the top log sets and the skeleton of the entire building. These are the seismic-stability improvements lacked by the Russian izba to become a building most resistant to earthquake shocks all over the world and at all times. With the above-mentioned vertical ties the bell tower can not be torn up into pieces or off the closed structure of the building even in case of very severe earthquake effects which was proved, by the earthquake in 1910. To my mind, it should not be doubted that the design of the underdome lanterns should be exactly the same, the dome shells being fastened to the frame of the building by metallic studs. In any case, during the same earthquake of 1910, the domes were drastically shaken which was indicated by bent crosses of the domes. In spite of this, the domes were not damaged. It were wise to secure the walls of the building and its skeleton exactly in the same manner, but I did not find out whether it had been done.

Now a few words must be said about the foundation. The cathedral church building is standing on a foundation slab laid of quary stone and lime mortar. The slab is faced with granite. The plinth wall of the building is also of granite. Structurally, it is like the Japanese pagodas: a wooden structure is standing on a stone slab, except for one curious element, i.e. the entire foundation is surrounded by a circular underground gallery. The purpose of this gallery is to stop the surface earthquake waves. It is known, that the house of Zenkov was also surrounded by a ditch providing an improvement of seismic stability. This was effective and his house was shaken less than the others during the earthquake. Exactly the same seismic-stability improvement was applied to the cathedral church. What was its origin? I think, it was not devised by Zenkov. It originates in some traditions of Central Asia. As an analogue, I recall an example of another time and from another distant continent. The most ancient and largest city of Mayas, Tikal (from the 6th century B.C. to the 6th century A.C.) was situated on the peninsula of Yucatan in North America. This peninsula is known for its high seismic activity [6]. 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 separated by deep hollows. What for are these hollows? Maybe they represent a seismic-stability improvement. During an earthquake, the surface course of the ground thickness is most shaken. The shaking rapidly diminishes with depth. When seismic waves encounter trenches and ditches, they are reflected, and the result is that a building surrounded by a trench stands as if in a calm zone. In short, the gallery surrounding the foundation of the cathedral church is also a seismic-stability improvement. The outstanding earthquake resistance of the cathedral church in the city of Verniy was ensured by the entire set of the above-mentioned seismic-stability improvements. All principles of earthquake-resistive construction have been met in this case, and if not so, an example is many projecting domed structures, sufficient measures are taken to compensate for this. Let us have some more talking about the wooden structures.

Again Wood

I may say once more that of all conventional construction materials the wood features the abilities of highest resistance to earthquake shocks. Only felt of Kazakh yurtas and animal skins as the material of Chukchi yaranga can rival the properties of wood. At present time, the wood's properties can be even surpassed by strong, elastic, light plastics capable of taking any shape, and also by pneumatic structures based on the properties of the air surrounding us. So the wood needs some more words about its applications in ancient structures.

One of the most ancient structures based on the wooden materials and used everywhere in Egypt, India, in the Caucasus, in Chine, and finds its applications today is a building having a wooden skeleton and fill of clay mixed with straw or animal wool. With a well made skeleton and light roof such buildings meet all the seismic stability requirements and stand well most severe earthquakes. Generally speaking, the ancient builders were good judges of wood, and it was not in vain, that the reinforcing of brick and stone structures with timber had been mentioned.

In this chapter I wish to relate to you some stories of interesting wooden structures directly intended for protection against earthquake effects. Generally speaking, there are lots of pretentious, richly decorated by carving, wooden structures in South-eastern and

Eastern Asia which we have not yet studied in our investigation of earthquake resistant structures. But, what new can be retold, compared with what has be related? Everything is wise and conventional from our point of view. The symmetry, light structures raised by flexible columns, and so on. Everything is in compliance with our principles. We may, perhaps, pay attention to a small temple of wood and stone, Mot Kot by name, in Vietnam, built in 1049. This temple is erected so that its base is a large round stone column. Eight inclined wooden beams corbel out of the stone column to support the timber columns supporting the temple and being the members of the skeleton of the entire building (Fig. 79) [22]. From the builder's point of view, the result is a point-supported building, the idea of point support being carried to its ideal, or ab surdity, 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 at so deep levels at which there are no surface waves at all. Therefore, in this event, there is no problem of allowing for the unequal motion of seismic field under the structure, like the case is with a long building. Second, due to the point support, no twisting will be conveyed to this building because of the nonuniformity of the seismic field. Third, the space seismic waves will be averaged along the height of the foundation column, and the vertical oscillations of this column will be minute. In short, this foundation column is an effective antiearthquake improvement. However, it is not so easy to erect, say, a 16-storey tower-type building on such a foundation column.

May be we shall find something of interest in China in which wooden structures were used from distant past times. Use was made in that country of the beam-post system forming gabled roofs. Unlike the European inclined rafters which produce thrust, the roof structure used in China (Fig. 80) produces no thrust, but adds much to the weight of ceiling. What is better is to be decided in each actual case.

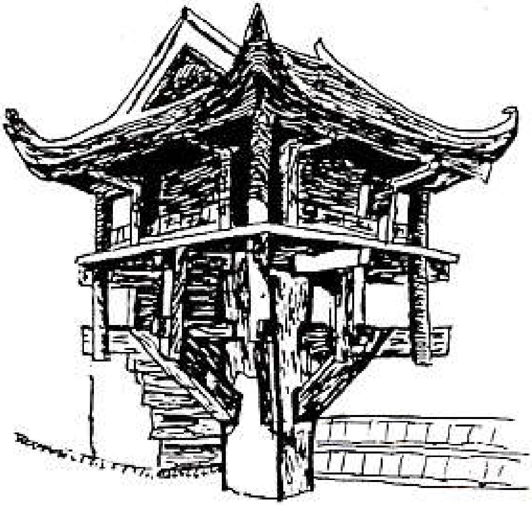

Fig. 79. Wooden Temple Mot Kot on Stone Column

Certainly, it will be good to find something unique in China, not seen anywhere. The only proper structure is the still surviving wooden pagoda of Sakya Muni of the Foguncy monastery built in 1056 in the province of Shansi (Fig. 81) [22]. The octahedral (in plan) pagoda is up to 66.6 metres in height. DEVILISH SKILL, DIVINE ART is written on a plaque fastened 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 probably of brick for the entire height of the ground storey. The wooden structures of the upper

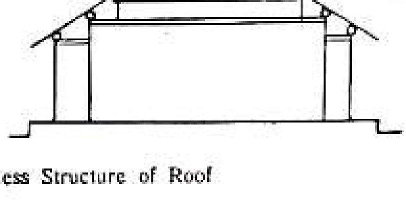

Fig. 80. Thrustless Structure of Roof

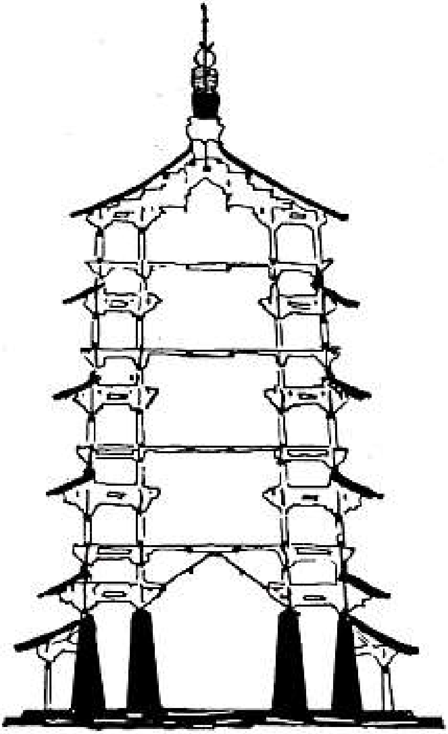

Fig. 81. Pagoda Sakya Muni Built in 1056

storeys of the pagoda rest on the octahedrons. All the joints of the pagoda skeleton are made ductile, their hinge devices are such that the joints are probably more flexible than those of the Japanese pagodas. 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 a moderate size 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. Shaken together with the ground will be the stone platform of the base with the rigid walls of the ground storey standing on the platform. Their amplitude will be the greatest, and 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 outstanding a device to damp oscillations. Nobody else could hit upon this idea. It is merely illogical. In order 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 metres by the unstable structures of wood to add to the weight of the entire structure contrary to the principles of seismic stability with the resultant pagoda of improved resistance to earthquakes.

It's enough. To my mind we shall not be able to find any example of more interesting wooden structure featuring a seismic-stability idea we are interested in. The wide abilities of timber materials in creating earthquake-resistant structures are clear from this short chapter. Let us proceed to the completion of our studies.

WHAT ELSE IS TO BE NARRATED?

Many facts that we may be interested in have been left beyond the scope of this book. Many facts could not be wormed out by me, many could not be tailored for this publication, though were known to me. I consider it necessary to set forth herein a few isolated examples of earthquake-resistant structures with a view to supplementing the contents of this book with some data from another viewpoint.

The barrel vault is a most ancient structural element widely used for spanning diverse structures from palaces and temples to drain ditches. In Mesopotamia starting with the ancient Sumerians, and ending with Iran of the early Middle Ages, long-used were barrel vaults of burnt brick for ceiling oblong rectangular halls of monumental buildings. Let us consider an example of this building ceiled by barrel vaults. An ancient architect deeply knowing the construction matter and being very determined left us the palace of king Khozroy I in Ktesifon which is the highest achievement in building vaulted structures during the Sassanid period of the Persian empire (Fig. 82). In the structure of this palace we are most interested in the 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

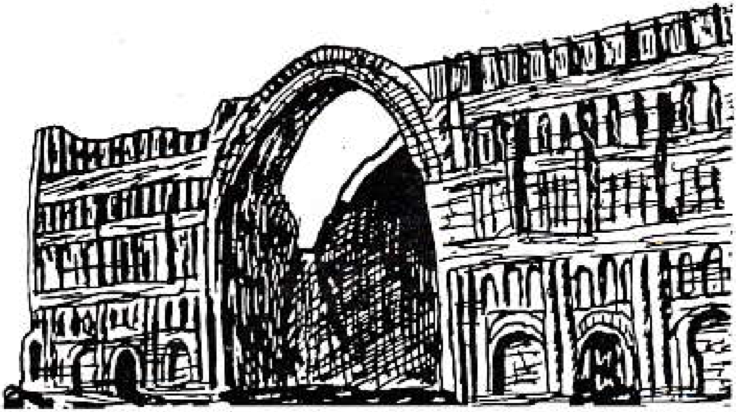

Fig. 82. Throne Room of King Khozroy

open at the front. It forms the ceiling of the king's reception hall. There is a vertical brick wall at the rear end of this vault. The other 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 to erect such vaults and how the king permitted it. There was no experience in constructing such huge vaults at that time. The largest dome of brick and lime mortar, which is generally easier than a vault to be erected, was built by that time in Chor-Kapu. Its diameter was 16.15 m. Note, to save brick, the walls of this structure were erected of crude stone which affected the seismic stability of the entire structure. We are interested in the structure of the vaults above the halls of king Khosrov not only because of their dimensions, but also due to the building improvements used in this structure, which allowed at least a part of one of the vaults to survive. Let us try to look into these improvements.

The king's reception hall ceiled by a gigantic brick barrel vault and open at the front is the architectural centre of the entire palace. The other hall ceiled by a similar vault is axially situated behind the first hall. Both vaults are not structurally connected with each other which is correct from the standpoint of seismic stability. The main problem the ancient architects were well aware of that concerned the whole of the building was to take up the thrust produced by the two heavy brick vaults. More than that, they knew that such vaults were erected for the first time and that the safety margin ought to be sufficiently large. This was done. The wall thickness at the wall to vault smooth joint was 4 m, and 7 m at the wall foot. The ancient builders considered these massive trapezoidal stable walls not enough to take up the thrust. Then, the building wings were erected in the form of vaulted and domed rooms whose walls were borne against the walls of the central vaults to provide additional support to these walls. As the time has shown 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 has survived. We must not be surprised at taking up the thrust caused by the brick vault, 27 m in span, 1 m thick in the voussoir joint and 1.8 m at the vault feet where it rests on the walls. Such a vault produces 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 have not yet mentioned the outline of the vaults in question. A surprise was being prepared for you. So, the gigantic vaults in question had an elevated outline whose configuration can be described from three centres, rather than the circular barrel outline described from one centre point of the more ancient vaults. The elevation of the dome or vault top, as you know, was a very important improvement from the standpoint of seismic stability, since it reduces the dome or vault thrust and thus reduces the weight of the load bearing walls and the whole of the building. With all the massiveness of the palace in question, its architect certainly was thinking it over 'how to reduce' the structure. There are no caissons, which are easy to form in the case of concrete technology of Rome, in this case, neither there is a thin brick shell with brick rigid ribs, because there is not yet skilled brick masonry we saw in Central Asia. Instead of all this, the structure was lightened by laying vaults of varying thickness. The vaults were most thin at the top voussoir joint and gradually thickened towards the vault foot where it rested on the wall. In addition, use was made of an elevated outline. The walls, as you also know, were also of varying thickness. The results were a lightened structure and uniform loading of its material. Thus, the problems we are facing today were being solved.

There is one more interesting detail in the example in question. The first vault above the king's reception hall has survived, while the rear vault collapsed long ago. What is the matter? Both vaults are similar in size and shape, quality and material. The answer to this enigma is to be found in some difference of the vault designs. This difference was casually mentioned by me. The first vault that has survived is more flexible, since there is no front wall of it, and its rear wall is standing separated from the vault. This large-span vault, not stiffened by ribs and walls, is sufficiently flexible to stand to unequal displacements of the massive walls occurring during an earthquake. At the same time, the rear vault reinforced by massive walls at both ends was destroyed. All this is in compliance with our principles of seismic stability. The elastic structures behave better than the rigid ones during an earthquake. Generally speaking, the buildings of that age had heavy domes, vaults and walls, the latter being nonuniform in their strength [44].

While this book was being written, it was reported that a very severe earthquake occurred in Iran at night from 20 to 21 June, 1990; a few tens of thousands of people were killed. It is interesting to know what happened to the throne hall of Khozroy and the mausoleum of Oljite in Sultaniya which have been mentioned above. Most likely, these buildings have survived, but received new "scars". Are they examined by anybody from the standpoint of seismic stability and paleoseismology? And this is very important particularly to the present-day construction.

The mysterious Scythians with their steppe burial-mounds, indomitable character, and gold articles in the "Animal Style", were not merely spirited cavalrymen.

They had their political system, their towns, and their skilled craftsmen and builders who were good judges of antiearthquake improvements. Not far from the modern city of Simferopol there existed a town, known as Naples of Scythians. Its excavation in 1946 revealed a stone mausoleum probably of famous Scythian king Scyllur who lived in the 2nd century B.C. I'll not speak about the seismic activity of the Crimea peninsula, this was known even to the Scythians who took it into consideration in their building work when led a settled life. Houses were built in place of yurtas, and urban mausoleums were erected above the graves of their military leaders in place of steppe burial-mounds. The following seismic-stability improvements have been used in the mausoleum under consideration. The wall stones were laid with bonding. One or two stones were laid longitudinally, and the next stone was edge-laid crosswise. Use was made of thick courses of clay mortar which imparts elastoplastic properties to the rigid stone masonry. At last, for reliable bonding of the longitudinal and transverse walls, L-shaped stones were laid in the building corners which had not been encountered yet anywhere. The walls up to 1 m wide are standing on a shallow foundation up to 0.4 m deep of broken stone. In this event again, as the case was with all the ancient builders, the foundation does not rest on the rock, but is supported by a thoroughly leveled course of ash. Timber is widely used in the mausoleum, mainly, in the flat ceiling structure and for reinforcing the upper part of the walls laid of adobe brick. Here the Scythians are [45].

Continuing our broken course narration, we shall set off for China. In this country I wish to draw your attention to the structure most resistant to earthquakes all over the world, which can compete not only with the modified Russian izba, but even with a building torn away from the ground with the aid of a balloon. The talk is about suspension bridges widely used in the mountainous regions. Their base is made up of cables or iron chains with cross beams laid on them. The decking planks were then fastened to the beams. The same chains or cables were used to make the railings connected to each other and the horizontal

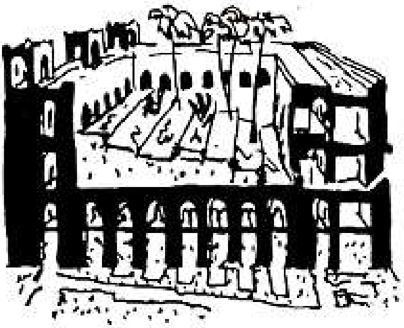

Fig. 83. Standing Rather Than Hanging Gardens of Babylon

decking by vertical bars. Reliable supports were laid on the banks. Some of those were furnished with special devices to control the tension of the cables. The length of the suspension bridges was up to 150 metres. Their width was 3 metres. The construction of such bridges was started in the 16th century, of which the chain suspension bridges were most durable. In 1701 the Ludintesotsyao bridge was built over the river of Dadukhe in the province of Sichuan. It was 100 m long and 3 m wide. Nine chains, 9 cm in diameter each, carried a wooden decking held on the top by two cables. The railings were also made up of iron chains. To my mind, even essential unlike motions of the bearing bank'structures will not be able to destroy this suspension structure. The Hanging Gardens of Babylon, one of the Seven Wonders of the World, though "hanging" are not "suspension" at all, as we understand it. This was merely a palace garden raised by a system of brick structures on a fenced roof of a building. It was built by the queen of Babylon Sammuramat (Fig. 83). All rich people of these hot areas tried to have such a garden.

In the flat lands of China, use was made of another type of bridges. These were arch-type multi-span bridges. The arches were of different shapes, from semicircular to elliptical and lancet. Special attention was paid to the strength of the bridge; to provide strong joints between the stone blocks, they were laid on lime mortar with bull blood and sticky rice added to the mortar to improve bonding. A specific feature of these bridges is that they were very frequently built in low lying localities, i.e. on poor grounds, plus earthquake hazards. All this was well known to the ancient architects who did their best to preserve their structures. In this event, in addition to strong masonry use was made of pile footing. More than that, to improve the reliability of the bridge structure, the bridge bays were made as if of a set of arches each of which could work separately, and if some arches were damaged, then the saved arches could take the bridge load. The eleven-bay bridge Lugoutsyao over the river Yundinhke is situated at a distance of 15 km from the city of Peking. The bridge is 235 m long, 8 m wide. It is decorated by 437 statues. The bridge is erected of lime slabs. This bridge existed already in the 6th-7th centuries. Marco Polo passed the bridges in the 13th century. This is one of the most famous and durable bridges of China.

Of various wonders of China we must mention the iron and bronze pagodas that were built there. The material of which a structure is erected plays an important part in providing the seismic stability of the structure. At that time the bronze and iron were the best materials from the standpoint of seismic stability. An example is a thirteen-storey pagoda laid in 1061 of cast-iron plates in the province of Hubei. Its height is 21 metres. This pagoda attracts our attention by its slenderness. Its height-to-diameter ratio at the foot equals 10, and the pagoda continues to stand winds and earthquakes. This only points to very good ties between the cast-iron plates. How are the ties designed? I myself wish to know it.

The Korean Pagoda in the monastery of Vontgaksa (1464) has a structure still more mysterious. The section of this pagoda varies with height in steps, rather than gradually, as usually. The lower three storeys are nearly similar to the base in the form of a twelve-pointed star. The seven upper storeys have a rectangular section far less in size. The result is a structure made up of two sections, one of which, the lower one, is rigid. The other section is flexible. The

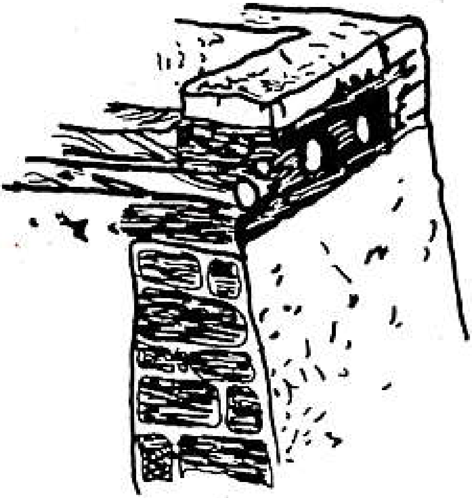

Fig. 84. Earthquake Resistant Joint Between Roof and Wall in Tibetan Dwellings

most mysterious in this case is the fact that the whole of the pagoda is made up of white marble, a brittle material. How are the parts tied to each other in this case? Whether they are tied in the Greek manner, by cramps and lead, or somehow else [22].

Of interest are the national traditions of Tibet, a zone of high earthquake activity. The houses were built there of cubical shape. The walls of these houses were widening towards their foot with a view to improving their stability. Timber post-beam skeletons were embedded in the walls. The method of placing the roof beams on the walls (Fig. 84) is a fact of most interest. Use was made of an elastic, damping device of boxwood roots. At the same time, this thick course of roots performed the airing functions.

It is high time to look to India we have not yet taken notice of, though that country has wonders not less than China does. There are temples there with flat and highly raised pseudo heavy domes, underground temples, mausoleum Taj Mahal, and domed mosques. You see, all these in the region of high earthquake activity. Of all these diverse examples, we shall choose only one example showing the desire of the Indian architects for making walls of their structures uniform and monolithic as it is dictated by the seismic-stability requirements. In the example under our study, this was achieved in a very simple way. The Kaylasa temple in Ellora was completely cut of a solid rock. Its dimensions are 50 by 33.2 by 32.61 metres. The world does not know another such a huge architectural monument fully out of a rock, like a statue. There is no need to discuss such important properties of earthquake-resistant structures as the uniformity of masonry, joint bonding and cohesion of mortar in this case [22].

The idea of obtaining monolithic structures by using large monolithic components was not foreign to Europeans. Known is the monolithic multiton dome on the tomb of Theodoric in Ravenna. The dome was cut as a whole in Istria and shipped to the site of installation [46]. The tomb of Theodoric looks like the tomb of Helen we have talked about before.

Now, we have America to visit, before it was conquered by Spaniards in 1519. It would be worthy of saying that the New World shows us other unique structures absolutely unlike to those we studied before. This difference is accounted for by the oceans separating the two worlds. On the other hand, there is something common to the human logic either of a Papuan, or an English lord. So, there is much in common between the building technology of Toltecs and Incas, and that of Egyptians and Greeks. Let us consider some examples.

One of the most ancient pyramidas, Kuikul'ko by name, was built before 500 B.C. This is a round, four-step, rather flattened structure having the following dimensions: the base diameter of 135 m and the height of about 20 m. The pyramid is laid of large boulders sunk in clay. This is one more example of a structure resistant to earthquake effects. The fairly flat loose massive of the pyramid body will breathe together with the earth 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 brick. To the point, they are related to the same time.

The largest pyramid in the world was erected by the Toltecs in Cholule. Its base dimensions are 300 by 320 metres. There are three pyramids more inside it. Each subsequent pyramid was erected as a superstructure on the previous pyramid which was covered with soil, stones, clay, and faced with stones. The result was that a huge massive was reinforced by a few courses of stone masonry. From the standpoint of seismic stability, it may be only welcomed. The above-mentioned gigantic pyramid in Cholule served as the platform under the shrine of Quetzalcoatl. The platforms under pyramids, temples and even under conventional houses were widely used by the peoples of the New World. These platforms were made of soil and clay, and were then faced with stone, for which reason they may be classified as soft by their mechanical properties in contrast to, say, a platform of large stone blocks that was made under the palace of Persepolis, an ancient Persian city, ceremonial capital of the Achaemenids. This platform was rigid. These platforms will behave in a different manner under effects of earthquakes. The soft platform serves as an seismic insulator like the clay paddings in Central Asia. The rigid platform averages, integrates an earthquake wave, cutting off its peaks. And, both platforms are seismic-stability improvements.

In the structures of Mayas, use was made of lime mortar, for which reason the core of walls, pyramids and platforms were made of rubble and soil flooded by lime mortar. This made it possible to erect higher pyramids resembling towers. One of the temples of Mayas in the city of Tikal was 70 m high. Voussoir materials were not known in that region, but wide applications were found by corbelled vaults constructed from opposite walls by shifting courses slightly and regularly inward until they met. This was done with high rise, exactly like the case was with the Regal tumulus we discussed above. More than that, the same tie beams of stone and timber were used as in the tumulus. The collonades, included in the complexes

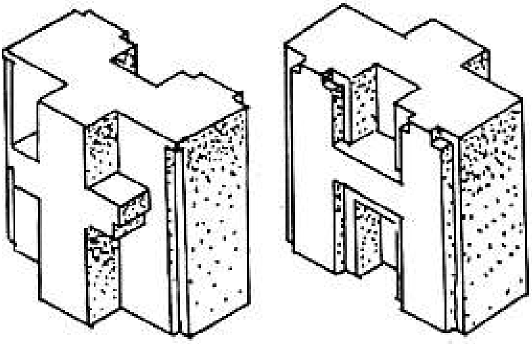

Fig. 85. Blocks Used in Ancient Construction of Temples

attached to the temples, consisted of columns assembled of separate drums connected to one another by a central wooden rod, like in the Greek temples.

It is necessary to say some words about civilization more advanced as compared to the civilization of Central America. This large urban and ceremonial site is situated high (3825 m above sea level) in the Bolivian Andes near Lake Titicaca. In the 3rd century the city of Tiahunaco was founded on the banks of this lake. The city consisted of three groups of buildings, each being erected on a gigantic ground platform faced with well processed stones. One of these platforms is 210 by 210 by 15 m. Gigantic blocks of some structures (Fig. 85) were found in good condition among the ruins of the third group of buildings named Puma-Punku - a double pyramid. The weight of these blocks is up to 200 tons. It is surprising that the blocks dressed with the aid of bronze tools only feature shaped configuration and accurate geometry. In assembly they accurately fit each other and have the appropriate recesses which allow them to be connected to each other by stone tenons and T-like bronze cramps. Though, all these ties are not lead sealed, as the Greeks did, the blocks are far larger, fit each other, and engage each other. The huge weight of these blocks resembles huge weights of the Egyptian structures.

It's over! Let it complete our studies of the ancient structures, though it makes me start another round by going from America to Spain to see Moorish structures, and then, perhaps, on into Africa, to Garthago, or maybe better again to Italy, to the Etruscans whom we have missed. Nothing has yet been said about the underground temples and cave settlements. It would be also of interest to study the behaviour of supertall structures during earthquake, say such as the Pharos of Alexandria, one of the Seven Wonders of the World. However, "a man can do no more than he can" says one of the English sayings.

To complete this book, we have to say something about the present-day seismic construction. This is discussed in detail by the work [47].

EARTHQUAKE-RESISTIVE CONSTRUCTION OF TODAY

Examples of the ancient architectural monuments were used by us to acquaint ourselves with the principles of earthquake-resistive construction and their structural implementation. Now, I think, you will not be very surprised by the following statement. At our eventful time, the new in the earthquake-resistive construction is represented by new construction materials and vast engineering resources, while there is nothing practically new as to the ideas of developing new systems providing seismic stability. Everything has been already used in some structural form. Maybe, the only new are building-robots which are equipped with special devices varying the parameters of the building involved with a view to reducing the earthquake loads as far as possible, depending upon the approaching earthquake waves.

So, as it has been mentioned at the beginning of the book, there are three methods of protecting buildings against earthquakes. The first, most popular, consists in making the building sufficiently strong and elastic, so that it can stand the earthquake loads without essential damage. The design of these buildings must satisfy the major principles of earthquake-resistive construction which we have discussed. The second method provides passive protection with the aid of various seismoinsulating devices used to separate the building from the ground to eliminate the earthquake shocks conveyed to the building and thus to reduce the seismic stresses occurring in the building. The third method provides active protection. In this event the building is equipped with its own program-controlled device which is used to eliminate fully or partially earthquake loads with the aid of the mechanisms under its control.

The first two methods of earthquake protection are today most popular and will be used still very long, while the third method refers to the distant future, though it is structurally implemented now, and we shall speak of it later. Into what the third method will develop, I can hardly imagine. Let it be done by some science fiction writer.

Superlight and superstrong construction materials will appear; new powerful power units will be built together with the relevant seismic instrumentation and programming devices. In any case, the system of active protection consists of three units. The first unit comprises the instruments recording an earthquake and transmitting the relevant signals to the second unit which is represented by a programming unit. The purpose of this second unit is to make a decision. If the earthquake is not dangerous to the building under protection, the other components of the system do not function. Otherwise, a command is sent to the third unit and appropriate measures are taken as dictated by the parameters of the approaching earthquake wave. For example, electromagnets can be used as the third, power unit. In this event, approach of an earthquake wave having an amplitude of 2.5 cm should make the electromagnets operate and raise the building for 3 cm to pass this wave under it.

The power unit may use jets of air, water, or whatever else. It will be still less complicated when an antigravitation screen will be invented. Then, turning on such a screen under the building will be enough

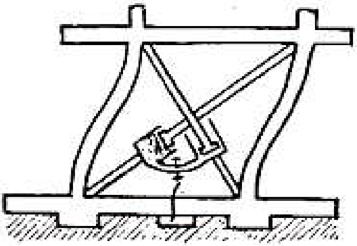

Fig. 86. Building-Robot

to smoothly raise the building above the earthquake forces raging underneath.

To provide active protection, the building not necessarily must go up above its foundation. This is a matter of distant future. Today, it is far easier to vary the rigidity characteristics of the building and thus its dynamic parameters, as dictated by the parameters of the approaching earthquake wave, so as to prevent oscillations close to resonance ones. An example is shown in Fig. 86 diagrammatically illustrating a device installed in the ground storey of a building which provides automatic tuning away from the resonance mode. The device was used in Japan [47]. Its operating principle is seen from the figure. There are diagonal links each of which includes piston elements. The piston cylinders are interconnected by a pipe through which the cylinder fluid flows, depending on the load of the diagonal elements. The diagonal links rigidity varies with the liquid flow rate. The next step is to control this flow rate. To this end, the pipe has a gate controlled by a programming unit which varies the structure rigidity so as to avoid resonance motions.

There exist still simpler designs of active protection systems. These are buildings employing special ties which disengage or engage. By this is meant, that in case of resonance motions, these ties must collapse or in contrary be engaged which will lead to changes in the rigidity of the entire building to eliminate its resonance [47]. As I have said it, we must expect these systems to be used in future. At present time, however, many designs are being developed and widely

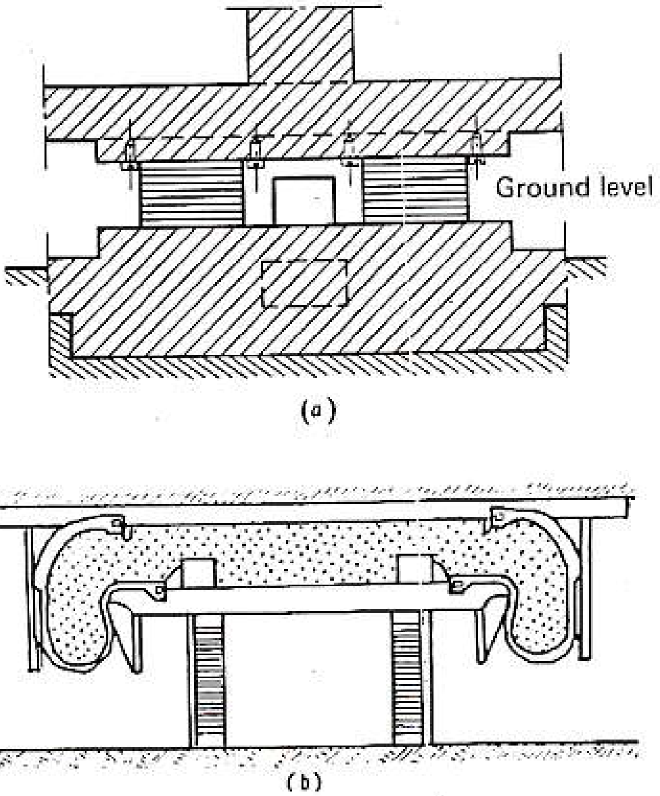

Fig. 87. Rubber-Metallic Seismic Insulators: (*a*) simple; (*b*) with air cushion

implemented, using systems of passive seismic protection whose purpose is to weaken the ties between the building and the ground. Conventionally, the passive system may be divided into two categories: one uses the sliding friction, the other - rolling friction. Examples are as follows.

Multilayer seismic insulators are most simple and most popular all over the world. These consist of metallic strips with rubber spacers between them (Fig. 87). Owing to the elastic ductility of these rubber-metallic seismic insulators, the foundation can move together with the ground during an earthquake, while to the building these motions will be conveyed damped. A disadvantage of this improvement is that the above-mentioned seismic insulator does not protect against the vertical component of earthquake effects. To improve its operation, a high-pressure air cushion is added to it which damps the vertical shocks (Fig. 87*b*).

The seismic insulators, next in simplicity, directly using sliding friction are the so-called sliding belts. These are made in the form of a series of supports located between the foundation and the bottom part of the building. Each support consists of two metallic or plastic strips not tied to each other. The lower strip is secured to the foundation, and the upper to the bottom surface of the building. During a fairly heavy and, therefore, dangerous earthquake, the earthquake forces will overcome the friction forces existing between the strips and the building will be saved by sliding relative to the moving foundation. You see that forces transmitted to the building cannot be greater than the friction forces. Because of this, to reduce earthquake loads conveyed to the building, it is good practice to reduce the friction coefficient of these seismic insulators. In Japan, for example, the metallic strips are oil coated which reduces the seismic load to one tenth its value without oiling. In China there are low buildings of brick "built on sand". In these buildings a course of specific sand is laid between the bottom beams of the building and the foundation to provide some sliding relative to each other. It is thought of to be enough to provide seismic stability even of low-quality buildings. In all these structures provisions must be made for elastic stops to prevent the building from sliding off its supports. If the friction forces between the building and the foundation are fully eliminated, no earthquake forces will be conveyed to the building. Generally speaking, this is feasible from the engineering point of view with present-day light construction materials. If a building is built so that it is floating in a pool with flexible walls filled with water, or another heavier liquid increasing the buoyancy force, we will obtain a universal seismic insulator protecting the building against all components of the earthquake effects.

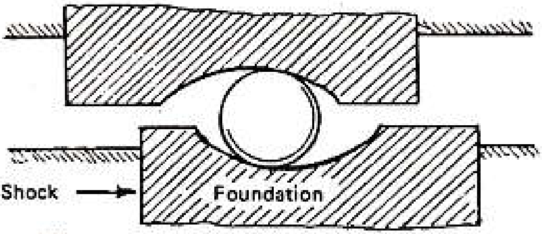

Fig. 88. Gravitational System of Seismic Protection

In order to reduce the same friction forces, use is made of seismic insulators with the rolling friction substituted for the sliding friction. All these consist of ball surfaces and, as a rule, are designed so that after an earthquake the gravity forces return the structures involved to their initial position. The application of theses insulators is more effective, bit their manufacturing is more complicated and costly. Probably, the most simple structure may be represented by balls, frequently of cast-iron, fitted between spherical surfaces (Fig. 88). Ellipsoids and more complicated bodies of revolution may be used in place of the balls. Their operation can be understood from the figure. To simplify making of these seismic insulators and avoid

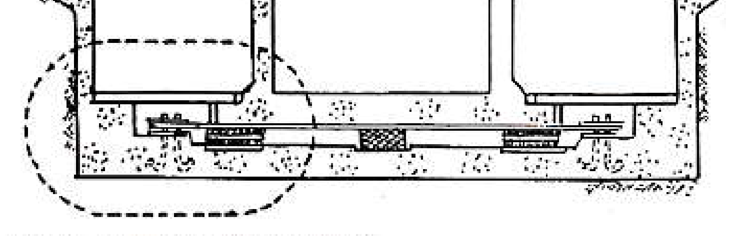

Fig. 89. Combined Seismic Insulator

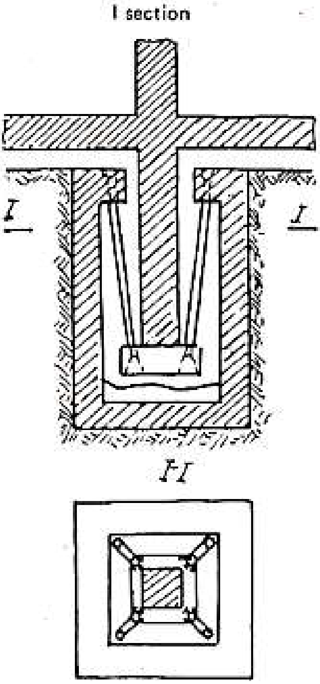

Fig. 90. Pendulum System of Seismic Insulation

making of curvilinear surfaces, use is made of simple roller supports with return to the initial position by means of springs, which was implemented in Canada (Fig. 89).

There exists also a pendulum (so it be called) method of seismic insulation. One version of this structure is shown in Fig. 90. In this case, a well is made in the foundation in which a slab is suspended. The slab bears a reinforced concrete column of the building. As a result, the whole of the building is suspended. To improve the damping effect of this pendulum structure, the well bottom is covered with sand. In case of this suspension, the building will have a far greater period of natural oscillations than without suspension. As a result, again the base part of the

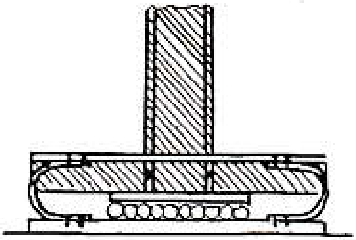

Fig. 91. One More Combined Seismic Insulator

building will oscillate during an earthquake, while the building itself will remain motionless due to its inertia. There are many versions of this structure.

Multistorey suspended buildings made a good showing during the earthquake of 1957 in the city of Mexico. These skeleton-type buildings were standing on solid reinforced-concrete slabs which were suspended from the headbands of metallic piles run through openings made in these slabs.

We have mentioned the major types of passive seismic protection elements to explain their operating principles. Note, that in practice none of the abovementioned elements of seismic protection is used in its pure state. It is good practice to use a combination of elements. Such a combined system used in the USA is shown in Fig. 91. It includes a roller support in the form of a two-row set of balls, and anchor bolts which are to be sheared, when the earthquake load exceeds a certain value at which the roller system of seismic protection must operate. It also includes a neoprene element used as the oscillation damper. Such a combination is used to provide the seismic stability of the building.

It is of utmost importance to develop systems of seismic protection for the structures of specific importance, such as bridges, atomic power station blocks, dangerous industry buildings. Certainly, the abovementioned systems do not cover the whole variety of what is invented and will be invented. The examples were used merely to show their operating principles.

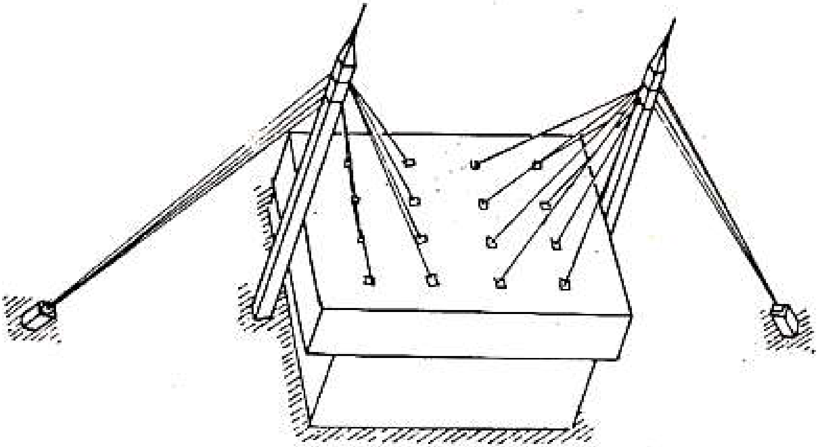

Fig. 92. Building with Suspended Ceiling

Here is one more interesting example of a long building with a suspended ceiling. This is a show hall in the city of Kitayusu, Japan. The hall ceiling is suspended from 16 steel cables arranged outside, along the longitudinal walls, eight cables from each side. The whole of the hall measures 173 by 43 m and consists of eight sections measuring 21.6 by 42.7 m. Each section is suspended from two cables (Fig. 92). The cables are supported in a hinge-like manner through elastic spacers. There are pile blocks at a distance of 25 m from the building in which the cables are anchored. The other ends of the cables are attached at the intersection points of the ceiling beams. The ceiling decking is assembled of lightened reinforced-concrete elements. The seismic stability of this structure needs not to be commented.

We have considered examples illustrating the systems of active and passive seismic protection, but we have not yet examined a conventional modern building whose seismic stability is ensured by its strength and correct design. An example in this respect is as follows. A 52-storey building, 212 m high, with four underground storeys is shown in Fig. 93. The load-bearing structure of the building is a single whole composed of three

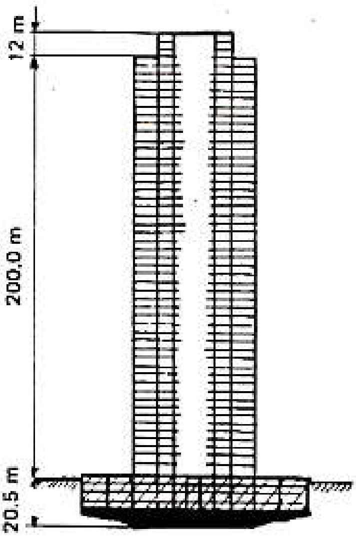

Fig. 93. Modern Tall Earthquake-Resistive Building

steel spatial frames. The foundation is a rigid reinforced-concrete slab. Next are two underground storeys of conventional reinforced concrete. The depth of the foundation exceeds 20 metres. The result is a land ship adapted to drifting among seismic waves. Like a sea ship having a deep draught is more stable, a building having a deep foundation of a pile base is less shaken by an earthquake wave, compared to a building having a shallow foundation, resting on the ground surface where the surface waves are more intensive.

This is a building that embodies all principles of earthquake-resistive construction. Not to mention the closed contours and flexibility of the entire structure, even from the size point of view, this building has a 2:1 ratio between the height and dimension of the foundation slab. The very simple design scheme of the building is resistant to earthquakes. The scheme is tested by multicentury experience, since it is similar to the Kalyan minaret in Central Asia described before. The scheme includes a rigid, deeply-laid slab of

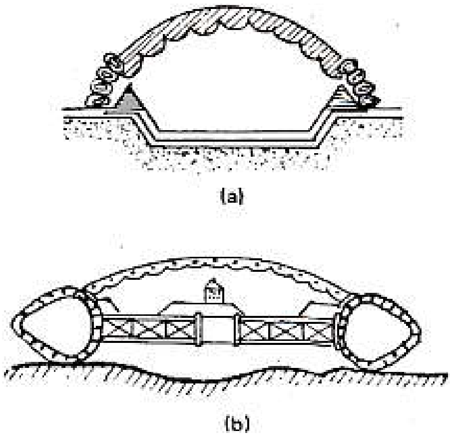

Fig. 94. Air Structures: (*a*) variable size; (*b*) supergigantic platform

foundation and the overground part of the structure secured to the foundation slab. The ancient builders laid it of brick, the present-day builders make it of metal. What is better? We must have a look at it. The metal is stronger, but the brick is more durable. It is not likely that a present-day metallic building will stand 800 years. Note, the ancient and modern architects adopted one and the same scheme of tall structures.

In conclusion of a very short survey of the present-day structures resistant to earthquake, let one more type be considered. These are structures providing the hundred-percent guarantee of their seismic stability, though they are difficult to be used for construction of dwelling houses. The principle of reducing the structure weight is practically absolute in them. These are most diverse air structures. In the USA, large-span aseismic air structures are under design for stadia, theaters, concert halls. The entire complex of a structure, say, a swimming pool, may be designed as an air structure. This complex will include the ceil and floor, inflated stands, and the swimming pool itself. The size of the structure may vary, depending upon the capacity required. As to the seismic stability, no restrictions may be imposed on the air structures (Fig. 94*a*).

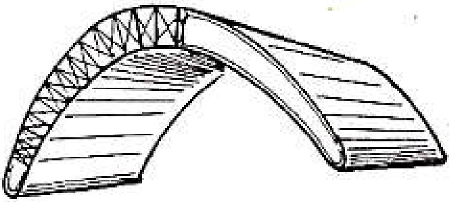

Fig. 95. Portable Double-Membrane Structure

There is a design of a fantastic helium-filled structure resembling a space ship of persons from another planet. It has an internal platform up to 500 m in diameter suitable for laying out equipment, buildings, and research stations. Referring to the Fig. 94b, this structure consists of roofing, a work platform, and a pneumatic support ring. With the aid of a helicopter the structure can be shipped to any site and installed on any ground. The elastic support ring isolates this structure from earthquakes.

Generally speaking, the pneumatic structures allow certain ideas of domed structures to be brought to their ideal. Recall that the double-shell dome of St. Peter's Basilica in Rome was structurally implemented with a view to placing the material where it works and getting rid of superfluous material in the central nonworking zone. To provide joint work of the shells, they were connected by ribs. Today this idea is made absolute in the pneumatic double membrane structures. Referring to Fig. 95, this shell, that may take any shape, is made of two membranes of air-tight material. The required inner space between the membranes is maintained by joint action of the tie strings and internal pressure.

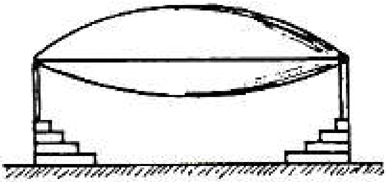

Fig. 96. Stationary Air Dome

Such air structures are used when it is required that the packing dimensions of structure to be shipped are small and easily installed. The illustrated structure was used as the pavilion shell at the show in Tsukuba, Japan.

The type of stationary air domes reinforced by steel cables is shown in Fig. 96. Such air domes can ceil spans up to 200 m having a 10 kg weight per m^2 of area being ceiled. Compare to the stone dome of Pantheon, a square metre of which weighs 7.3 tons. The air structures cannot stand well to typhoons and snow loads, but they well put up with earthquakes, and we well understand why it is so [47].

The light domes can be made of light metals, fiber glass, and the like. In short, the earthquake-resistive construction of our time is far more feasible, as regards the availability of required construction materials and construction technology rich in various mechanisms. It depends upon us, our accuracy, erudition, humaneness, and our will to perform construction jobs with maximum seismic stability possible.

SUMMING UP

To my mind, the offer of this book to consider the ancient structures, using the present-day idea of earthquake resistance of structures has come up to its purpose.

The variety of ancient structures was used to illustrate different approaches to the construction of aseismic structures. Using examples of past times, it was easy to show that the antiearthquake protection is rather a wide notion.

It is far from being merely improving the cement brand and incre asing the amount of reinforcing material used as is supposed today by many, even specialists.

It is an entire system of improvements aimed at saving buildings during earthquakes and increasing their durability.

This is actually the subject of this book in which I attempted to create a positive character of the ancient builder to be imitated by the modern builders, and to show that the ancient architects had much to be studied.

Whether it is a success, you're the best judge of that.

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