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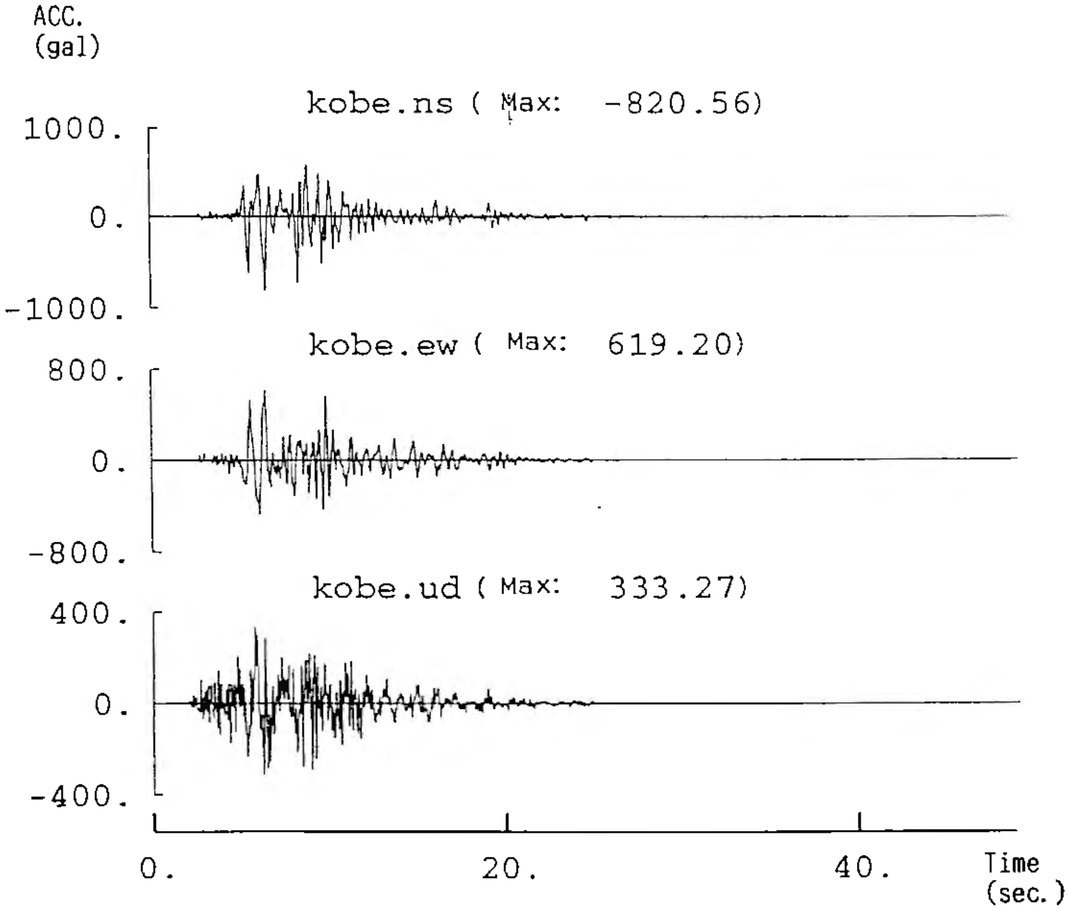
DESIGN
FOR
EARTHQUAKE AND WIND



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DESIGN FOR EARTHQUAKE AND WIND

Introduction

As you recall, the title I accepted at the IMIA Conference last year was "Design Standard for Earthquake and Wind." Since then, my scrutiny of the title has prompted me to exclude the term *standard*, as I have realized that design for earthquake and wind, still unexplained natural phenomena even at the end of the 20th century, is a matter of repetitive trial and error and thus is far from being firmly defined in a strict sense.

The concept and method of design actually vary in accordance with kinds, functions and the respective meaning of structures or constructions. Moreover, numerous elements are involved, such as the history, culture and social trends of the communities or nations where the structures or buildings are located, requirements for security, economic demands, the experience or preference of the designers, and so forth. A design standard may exist for the design of machinery and equipment or housing that is mass produced or of particular construction. But the design standard in these instances is solely restricted to certain aspects of construction, as in the case of earthquake or wind resistant design. While my deletion of the term *standard* stems from the judgment that it is next to impossible to deal fully with such a big issue within the context of this paper and the time available, I should perhaps also mention that the scope of our research, or as I would put it, *playground*, should be wider, insofar as practicable, so as to allow taking a host of relevant issues and following through positively thereafter.

1. Links Connecting Natural Disasters and Human Society

Ever since our ancestors attempted to build houses by their own hand, emerging from natural caves or the shade of rocks, earthquake and wind resistant design has probably been a chronic concern, beginning with sun-dried brick and tents.

In any case, earthquakes and wind storms are natural phenomena, not disastrous in themselves. When a huge earthquake occurred, no calamity ensued in a place where no inhabitants lived and no buildings existed. Nevertheless these natural phenomena are regretfully tough nuts to crack. Even after racking our brains for countermeasures, we can hardly survive disaster, once typhoons or gigantic earthquakes raid human society. In fact, new countermeasures create new disasters.

Along with the complication and the larger scale of the hardware and software of human society through the advancement of scientific technology, disasters may occur in which the damage is immense in scope. All structures on the globe are subject to both the constant power of the vertical gravity of the earth and the temporary power of earthquakes or wind horizontally applied. We are able to address the former rather easily as its strength is constant, but appropriate measures are hard to find for the latter, owing to the fluctuation of power and the irregularity of nature. Despite the abundant knowledge obtained from the experience of Homo Sapiens through 40,000 years of history on the earth, and even with analytical research employing up-to-date scientific skill and the availability of super-computers, we still have to

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admit that natural phenomena present us with numerous unresolved problems. Many scientists in this connection never fail to remark after an earthquake, "We realize again that there are still a lot of things we don't know." We are bound to hear the repetition of this statement in the future.

2. A History of Antiseismic Law

To begin with, archaeology.

The following is from the *Encyclopedia Britannica,*

"the military and political achievement of Hammurabi in finally establishing a central and efficient Government at Babylon, which included not only Sumer and Akkad, but extended northward to the central provinces of the Tigris and Euphrates, must be regarded as one of the most far-reaching events in ancient history. Henceforth Babylon was to be the political and intellectual centre of West Asiatic history right down to the Christian era. His name is particularly associated with the great law code promulgated for the use of the courts throughout the empire."

Historically, the stipulation regarding builders appeared in the Hammurabi Code (Articles 229–233) enacted some 4,000 years ago, in the 18th century BC, as follows:

Article 229: Should the owner of the house be dead by the collapse of the house which was not strong enough in construction, the builder must be killed.

Article 230: Should the son of the house owner be dead by the collapse of the house, the builder's son must be killed.

Article 231: Should the slave of the house owner be dead by the collapse, the builder must offer an equivalent slave.

Article 232: Should the furniture and effects be damaged by the collapse of the house, the builder must compensate all the loss sustained. The fallen house which was not strong enough in construction must be rebuilt by the builder at his own cost.

Article 233: If the wall of the house is on the verge of crumbling due to inadequate construction, the builder must reinforce and repair the wall at his own cost.

These are straight forward "an eye-for-an-eye" and "a tooth-for-a-tooth" penalties. It may however be questioned whether they are really laws in our sense. The stipulation that if the house was not strong enough in construction makes the Hammurabi Code stringent by assigning to the architect in ancient Babylonia a heavy responsibility, i.e., business was a matter of life or death for the architect.

This is the oldest law on architecture, the purpose of which is very clear. As stated above, vast Babylon included the active earthquake zone of central Asia, extending from Turkey to the Himalayas via Iran. And it could be the oldest earthquake and wind resistant code, assuming the occurrence of strong winds.

Another historical anecdote is found in Deuteronomy 22:8 in the Old Testament. It says, "When you build a new house, put a parapet along the roof, or you will bring the guilt of bloodshed on your house if anyone should fall from it."

According to *Earthquake and Volcanic Eruptions*, an impressive masterpiece compiled by the Swiss Reinsurance Company, the concept of modern antiseismic construction was set forth by Leonardo da Vinci for the first time some 500 years ago, and the first antiseismic construction rule was applied in Lisbon after a big earthquake in 1755.

Regretfully, I am not knowledgeable about the design concept of Leonardo da Vinci cited by the Swiss Reinsurance Company, and, furthermore, while Mesopotamians constructed bridges of wood as well as stone from 4,000 to 3,000BC, and though not so old, ancient Romans built water supply bridges after 300BC, I also do not know what sort of theory on antiseismic and wind resistance they possessed.

Next, let's look at the modern aspects of rules of this sort. I first quote the Building Law of Japan and then will refer to S*implified Building Design for Wind and Earthquake* by James Ambrose, etal. Univ. of Southern California, Los Angeles.

The Building Standard Law of Japan sets forth the following stipulation.
"Article 1. (PURPOSE) The purpose of this Law is to safeguard the life, health, and property of people by providing minimum standards concerning the site, construction, equipment, and use of buildings, and thereby to contribute to the furtherance of the public welfare."

The latter includes the following.
"It should be noted that building code criteria in general are developed with a particular concern in mind. This concern is not for the preservation of the building's appearance, protection of the general security of the property as a financial investment, or the assurance that the building will remain functional after the big earthquake--or, at the least, be feasibly repairable for continued use. The building codes are concerned essentially--and pretty much only--with life safety; the protection of the public from injury or death. Designers or building owners with concerns beyond this basic one should consider the building code criteria to be really minimal and generally not sufficient to assure the other protections mentioned previously, relating to the security of the property."

While we believe the foregoing is overstated because there is a correlation between preserving both the safety of structures and people, we have to admit that the building code criteria constitute the minimum stipulation under the law and structures built following these criteria are not necessarily safe.

3. Flexible or rigid?

What are the specifics of antiseismic design?
The historical development of modern antiseismic design may have originated in Japan and the West Coast of the U.S., both of which are earthquake prone areas. In the 20th century, the

history of antiseismic design underwent contrastingly interesting developments in the U.S. and Japan.

Events that triggered the development of Japanese antiseismic design were the San Francisco Earthquake in 1906 (M8.2) and the Great Kanto Earthquake in 1923 (M7.9).
The specific method of Prof. Toshitaka Sano of the University of Tokyo, the "Theory of Earthquake Resistant Construction for Houses," was made public in 1914. After surveying the damage of the San Francisco Earthquake, Prof. Sano introduced the concept of "seismic coefficient" for the first time. He defined the seismic coefficient as the ratio of earthquake acceleration to gravity acceleration. This was a daring and fairly practical invention for antiseismic design, replacing the complicated and dynamic seismic force with static force, the strength of which was assumed by multiplying the weight of the structure by the seismic coefficient.

At the time the revision of the Urban Building Code of Japan was made, just after the Great Kanto Earthquake, September 1, 1923, the "seismic coefficient method" advocated by Prof. Sano was adopted as the antiseismic design method under the law, which formulates the seismic coefficient 0.1 under the "allowable strength (the elastic limit)."

The Urban Building Code of Japan had limited the height of the buildings to less than 31 meters since 1919; the limitation was not for earthquakes but for avoiding the overcrowding of cities. This height limitation remained until the switch from height restriction to limitation of floor area ratio with the revision of the Building Standard Law in 1963. As soon as the enactment of antiseismic legislation was made in 1923, a dispute on the rigidity of the structure cropped up in the Japanese construction world into two groups, ***flexible or rigid***. Since no high buildings were in existence due to the height limitation and the use of rigid steel-framed reinforcing-rod concrete peculiar to Japan, it was not thought necessary to conduct dynamic analysis. Also as regards the antiseismic design standard, there was conceit in that the design seismic coefficient of 0.2 (0.1 was changed to 0.2 in 1944) within working stress design was the most rigid standard in the world. As a result, Japan lagged behind the U.S. in the development of a dynamic design method, which was realized after the abolishment of the 31-meter height limitation in 1960.

In the U.S., M. A. Biot of the California Institute of Technology came up with the concept of "Response Spectrum" of seismic motion in 1932. G. W. Housner further developed this concept and investigated how flexible structures with a long natural period shake at the time of an earthquake by analysis of records of the Long Beach Earthquake in 1933 and the Imperial Valley Earthquake (El Centro) in 1940 using strong motion seismography, which was applied for the first time. Housner also dealt with this in his treatise "Characteristics of Strong-Motion Earthquakes," in which the concept of the characteristic of maximum elastic response and elastic response spectrum were presented. This concept was reflected in San Francisco City regulations in 1956, thereby reducing the base shear coefficient of buildings with a long natural period to a shorter one, in the course of which base shear was fixed in accordance with primary natural period. Coupled with the advancement of the computer, the dynamic antiseismic design method since then has steadily advanced and has been widely adapted on a world scale as the basis of an antiseismic design method.

After the Northridge Earthquake the *Los Angeles Times* dated Feb. 16, 1994 reported on the comparison of California freeways and Japanese expressways, a part of which reads as follows. "Japanese expressways are squatter and more massive than those in Southern California. Japanese designs generally require more steel in columns and spans, and more concrete. Engineers debate whether highways designed that way will be flexible enough to move to the forced rhythm of an earthquake. But there is no doubt that the additional material adds to construction costs."
It is interesting to note that differences in development of antiseismic design may continue to influence the basic design concept of structures by the engineers of two countries.

4. Laws and Regulations on Antiseismic Design

While numerous laws, regulations and standards regulating antiseismic design are in effect, they have been revised over time in accordance with the advancement of technology and experience of earthquake disasters, examples of which from Japan are as follows.

- Enforcement Ordinance of the Building Standard Law. Ministry of Construction
- Auditing Standard for Antiseismic Design for Nuclear Power Reactor Installation. Nuclear Safety Committee
- Antiseismic Design Criteria for Highway Bridges. Ministry of Construction
- Standard for Antiseismic Design for High Pressure Gas Plants. Ministry of International Trade and Industry
- Notice Providing Technical Details for Regulation of Dangerous Goods. Ministry of Home Affairs
- Guideline for Anti-earthquake Code for Electric Facilities in Substations. Japan Electric Association
- Notice Providing Technical Details for Oil Pipelines. Notification of Ministry of International Trade and Industry, Ministry of Transport, Ministry of Construction and Ministry of Home Affairs
- Guideline for Anti-earthquake Construction of Water Supply Systems. Japan Water Association
- Anti-earthquake Design and Standard of National Railways (Now Japan Railways). Japan Railways Facilities Association

etc.

The basic concept on antiseismic design is subject to the new antiseismic law of 1977 of the Ministry of Construction, which extensively adopted dynamic theory. The standard laid down earlier was thus revised after 1977. For instance the antiseismic design criteria for highway bridges were revised in 1971 and 1980. Furthermore, subsequent revisions will be made in the wake of the lessons from the Great Hanshin Earthquake.

Humans have lived through a number of great earthquakes and the resultant disasters and learned much from them while making a lot of sacrifices. The Great Hanshin Earthquake (M7.2), which hit the western part of Japan in January, 1995, claiming more than six thousand lives, came as a great shock to the Japanese people, particularly to disaster professionals in governmental, private and academic sectors. Since our acquisition of up-to-date antiseismic technology, we have experienced repeated earthquakes but the damage was far greater than we could have imagined from past earthquake disasters. The quake paralyzed the local administrative services that should have been offered in an emergency and damaged the network of water mains so badly as to disrupt fire fighting. It sheared many of the bridge piers of expressways and railroads which had been considered antiseismic according to Japan's earthquake-resistant design specifications, supposedly the most stringent in the world. The scene brought home to us the horror of a large earthquake right beneath a major urban area. The experience has to be put to good use. Throughout Japan large-scale strengthening work is now being done on piers and other components of existing expressways and railway structures which were designed and constructed prior to the revised antiseismic design law of 1977.

In fact, in the case of the Great Hanshin Earthquake, more than 80% of the collapsed reinforced concrete bridge piers of highways were designed and constructed before 1964. Warnings had been made to retrofit and upgrade the old-standard highway bridges by engineers, professors and others, who inspected the freeways damaged by the Northridge Earthquake in 1994 in Los Angeles. Subject to these warnings, enforcement work targeting old bridges was already started on a step-by-step basis, but unfortunately the bridges in the Kobe area had been put off until later.

It was indeed fortunate that most of the buildings constructed to the 1981 revised version of the Building Standard Law of Japan, except those which were out of balance or of poor workmanship, escaped serious damage. The painful experience acquired from the disaster in Kobe with a population of 1.5 million offered valuable lessons in organizing preventive measures against a possible disaster in the future in a metropolitan area populated by more than 20 million people.

For your reference, the following is an excerpt from information submitted by courtesy of the Munich Reinsurance Co. on problems regarding the Uniform Building Code as revealed by the Northridge Earthquake which took place in 1994, just one year before the Great Hanshin Earthquake:

> "About 400 steel frame buildings are located in the area affected by the Northridge earthquake. More than 100 have been inspected so far, the majority show some degree of damage to the steel frame (cracked base plates, column flanges cracked, fractured welds). Several factors contributed to these failures:
>
> (a) The nature of the earthquake (trust fault event with up to 2.3g horizontal and 1.7g vertical acceleration) that exceeded the design code by a factor of 2 or 3 in some regions. In the Northridge quake, ground motion and acceleration changed within short distances, even as little as 100m.
>
> (b) The design prescribed by the Uniform Building Code (UBC) for welded beam connections obviously needs improvement. Some engineers believe the UBC prescribed a flawed connection.
>
> (c) The use of steels that have too high yield strength; the connection fails before the steel

yields.

(d) The poor welding quality of many connections. Several weld failures are brittle fractures at low stress level. Welds are in general a weak link and need careful execution, proper procedures and quality inspections.

Damage to weld connections has reduced general confidence in steel frames, previously regarded as the best design for quakes.

The American Institute of Steel Construction (AISC) issued interim guidelines for beam connection repair (adding steel plates to beam flanges). AISC's recommendations have been validated by tests carried out at the University of Texas/Austin. Proposed method is three times costlier than present beam to column connection. The California Seismic Safety Commission considers the suspension of the UBC subsection dealing with welded beam flanges and the issue of interim guidelines. Engineers have proposed to avoid prescription but to provide performance based rules (Winfried Neise. U.S. Branch of Munich Reinsurance Co., Nov. 21, 1994)."

The IAEE (International Association for Earthquake Engineering) has published *Earthquake Resistant Regulations–A World List–1992* which carries on the laws and standards for ordinary buildings etc. in 37 countries ranging from Algeria to former Yugoslavia, from which I quote the part on the French AFPS90, "Recommendation of rules relative to the structures and installations built in regions prone to earthquake."

"The *rules PS 69* (D.T.U.) in force for the time being have embarrassing deficiencies in this respect and may even, in certain cases, prove to be inadapted. The necessity to cover as far as possible the whole range of situations likely to occur, as well as to get the most out of the evolution of knowledge impose a total recasting of the document."

These prescriptions imply that the field of validity of the technical rules in use today shall be greatly extended.

Now that the antiseismic standards have been kaleidoscopically changed for individual cases, it is essential to confirm which standard was applied in analyzing the antiseismic design of structures or buildings.

Note: Consisting of 25 volumes, a series of reports on the Great Hanshin Earthquake is now jointly being prepared by the Architectural Institute of Japan, the Japan Society of Civil Engineers, the Japan Society of Soil Mechanics and Foundation Engineering, the Seismological Society of Japan, and the Japan Society of Mechanical Engineers. Based on intensive on-the-spot investigation by experts with the focus on architectural and civil engineering aspects, they will include reports describing damage to factories into which no outsiders are usually allowed. Containing 500 pages, each volume will offer both Japanese and English versions. To be priced around ¥800,000 in complete form. No definite date for publication has been announced yet, but they will be available within a year.

5. Antiseismic Design

Rapid release of strain accumulated in the crust of the earth and concurrent occurrence of a seismic wave are phenomena occurring in an earthquake. The seismic wave transmitted in every direction and vibrating the surface as well as the subsurface is the earthquake ground motion. The extent of a structure's damage from earthquake ground motion is attributable to the characteristics of the earthquake ground motion and to how the structure responds to it. For antiseismic design intended to minimize damage, an appropriate appreciation of the earthquake ground motion for design purposes and understanding of the antiseismic design method, which includes the response of structures to it should be made.

5.1. Design Earthquake Ground Motion

Regarding design earthquake ground motion, a review is conducted under the Building Standard Law of Japan which is the most stringent specification in the world and in addition under the regulations for the nuclear power installations.

Designed earthquake ground motion of buildings is to be carried out according to the Building Standard Law of Japan as follows.

5.1.1. The Building Standard Law of Japan

First step design

Earthquake design ground motion for medium earthquakes of comparatively high frequency (seismic intensity 4 to 5 on the seismic intensity scale of the Japan Meteorological Agency): confirmation of security shall be made for elastic design, usually based on allowable stress design aimed at preventing building material from entering a yielding area.

This enables the building to maintain its function, without damage, in a medium earthquake, approximately 80–100 gal at the maximum acceleration of the design earthquake ground motion. The size of the seismic coefficient puts the base shear coefficient (C_B) at 0.2.

Second step design

Earthquake design for large earthquakes occurring rarely will inevitably allow minor damage to a building. It should not endanger people by the collapse of the building, heavy breakage or subsequent calamities.

For large earthquakes, the ultimate strength and plastic deformation capacity of the frame should be evaluated as it is, as far as possible, in the calculation of which the elasto-plastic response capacity of the structure against large earthquakes is done from the standpoint of security. In this case, establishing the allowable degree of deformation is the pivotal issue. The second step design assumes a large, disastrous earthquake of seismic intensity 6–7 and about 300–400 gal, and the design shall be made subject to the elasto-plastic design method, taking into consideration the plasticity of materials.

The building may crack but still safeguard human life in a collapse. The seismic coefficient is put at C_B=1.0.

For buildings over 60 meters in height, the law shall require a stricter design standard. The structures exceeding a height of 60m are customarily done according to the dynamic design approved by the Construction Minister. These are LEVEL Ⅰ, providing elastic design with maximum acceleration of 200–300 gal, and LEVEL Ⅱ, which hypothesizes of 300–500 gal by

the elasto-plastic design method.
Seismic coefficient = 0.15/Tsec–0.3/Tsec, minimum 0.05 (T: Natural period)

At the second design stage the restriction of deformation, form, securing of yield strength ductility and investigation of lateral antiseismic strength are to be done. The structures are to be categorically classified for buildings with a height from 31m to 60m or as other buildings less than 31m in height, which requires the above checks.

5.1.2. Nuclear Power Installation

Nuclear power installations are subject to the most stringent earthquake ground motion design, details of which are as follows.

Earthquake ground motion S_1
The earthquake among recorded earthquakes that would have the greatest effect on the proposed site and surrounding region and which may occur again in the same fashion, or among those earthquakes that might be induced by highly active faults in the near future.

Earthquake ground motion S_2
The earthquake among those earthquakes exceeding the maximum design earthquake that would have the greatest effect on the proposed site based on engineering judgment following a seismological review of past earthquakes, the nature of any active faults and the seismotectonic structure underlying the site and the surrounding region.

5.2. Principle of Antiseismic Design Method

The following is a rather detailed sketch of technical theory on prevailing typical antiseismic design methods, which is the foundation for antiseismic design.

5.2.1. Static design method

5.2.1.1. Seismic coefficient method

The calculating method replaces the seismic force with the static load (inertial force) operating on the structure. Since the analysis of the structure's safety and calculation of stress against each part of the structure can be made in a conventional manner, this method is very practical as well as effective for the antiseismic design of rigid structures on the ground where the natural period is relatively short (less than 0.1 second).

$$K_B = \beta_1 \times \beta_2 \times \beta_3 \times \beta_4 \times K_0$$

K_B: Design lateral seismic coefficient
K_0: Standard design lateral seismic coefficient
β_1 : Seismic hazard zoning coefficient
β_2 : Soil classification coefficient
β_3 : Structural factor
β_4 : Importance factor

This structural factor β_3 is the factor for simply structures such as wooden houses, reinforced concrete buildings or steel frame and slate buildings, which, unlike the response magnification factor, does not take into consideration the response characteristic of the structures.

5.2.1.2. Modified seismic coefficient method (Quasi-dynamic method)

The application of the seismic coefficient method runs into difficulty for flexural structures like long-span bridges and high-rise buildings as their response to earthquake and wind motion is different from the earthquake ground motion. This method adopts the equivalent seismic coefficient of the method mentioned above with the modified seismic coefficient taking into account the vibration characteristics of the structure. This method is employed for antiseismic design of comparatively important structures.

First, fixing the natural period of the structure, the corresponding base shear coefficient is decided, taking into account the type of soil, etc. By multiplying the total weight of the structure by this base shear coefficient, shear force by seismic force acting on the base of the structure is fixed. The total of this shear force shall be distributed over the height of the structure in the appropriate manner (see below).

The way of deciding dimensions of structural components in accordance with the structure standard is the same as the seismic coefficient method, where this stress of structural component caused by the distributed seismic load is added to the dead load, and thus calculated load shall be designed within the allowable strength of the component regulated by the material and structural design standard.

This is the mathematical formula:

$$C_B = \beta_1 \times \beta_2 \times \beta_4 \times \beta_5 \times K_0$$

C_B: Base shear coefficient, which is the modified lateral seismic coefficient considered to be the natural period

K_0: Standard design lateral seismic coefficient

β_1: Seismic hazard zoning coefficient

β_2: Soil classification coefficient

β_4: Importance factor

β_5: Response magnification factor fixed in accordance with classification of soil, natural period and damping factor

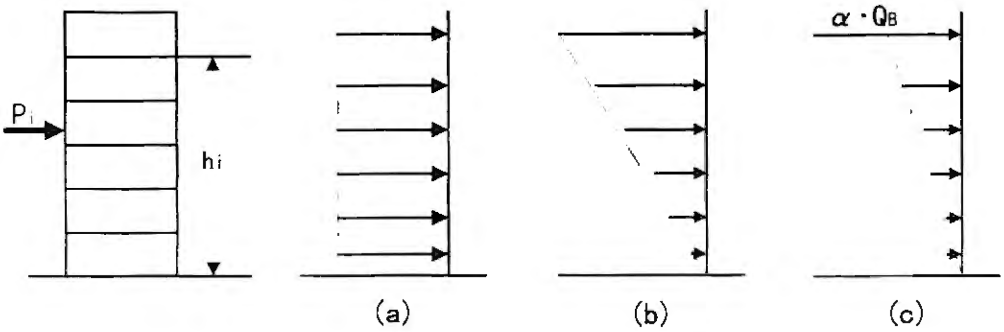
As mentioned above this shear force is to be appropriately distributed vertically. Examples of seismic force distribution methods are as follows.

1. evenly and vertically
2. in an inverted triangle which becomes larger as the height increases

and

3. the method in which part of the seismic force (10%–25%) is concentrated on the top part, and the rest of which is distributed in an inverted triangle.

weight of i-th story	w_i
height up to i-th story	h_i
base shear coefficient	C_B
number of stories	n



Base shear $$Q_B = \left(\sum_{i=1}^{n} w_i\right) \cdot C_B$$

Distribution of seismic force (P_i)

(a) $$P_i = w_i \cdot C_B$$

(b) $$P_i = \frac{w_i \cdot h_i}{\sum_{j=1}^{n} w_j \cdot h_j} \cdot Q_B$$

(c) $$P_i = \alpha \cdot Q_B + (1-\alpha)\frac{w_i \cdot h_i}{\sum_{j=1}^{n} w_j \cdot h_j} \cdot Q_B$$

Story shear force $$Q_i = \sum_{j=i}^{n} P_j$$

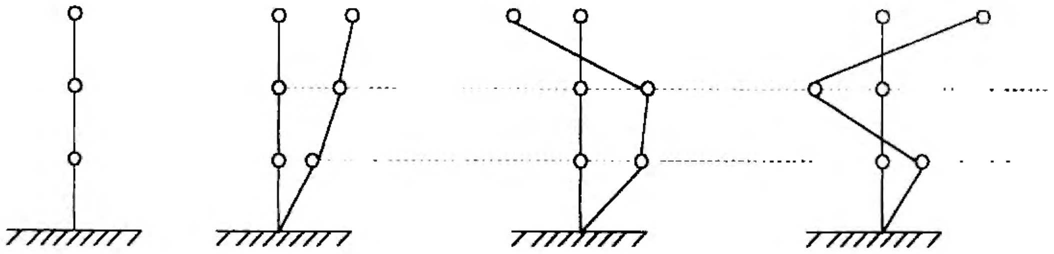
Story shear coefficient $$q_i = Q_i / \sum_{j=i}^{n} w_j$$

Overturning moment $M_i = \sum_{j=i}^{n} P_j \cdot (h_n - h_j)$

A combination of the inverted triangle distribution and the top part concentration are applied for the first mode and high grade mode. The concentrated load of the top part reflects consideration for the whipping phenomenon of a building with a long natural period.

While there is the view that the modified seismic coefficient method should be included in the category of dynamic design method, this does not take into account the time factor on the response of the building. That is, response of the building to external force creates a time lag and time of the maximum value varies with the height. But in view of the fact that this design method ignores this factor and treats the seismic force as static external force, it can not be regarded as dynamic design.

5.2.2. Dynamic analysis method



Mode:	1st mode	2nd mode	3rd mode
Period:	T_1	T_2	T_3
Participation Factor:	β_1	β_2	β_3

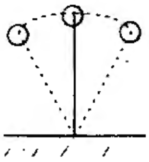
(3 modes of a 3 degree-of -freedom system)

Generally, dynamic analysis is necessitated for bridges (diagonal suspension bridges, suspension bridges, high pier bridges), where the multi mode of vibration can not be ignored, and also for structures such as high-rise buildings, where design taking into consideration the first mode only is not appropriate.

Because of the need for detailed antiseismic study, dynamic analysis is frequently applied for structures with complicated vibration characteristics and for such highly important structures as nuclear power stations. The principle of dynamic analysis is applicable to the solution for the equation of motion of vibration systems, for which various methods are available.
The following is the most simple example of the basic equation for the single-degree freedom system, and furthermore below are examples of various dynamic analysis.

$$m\ddot{x} + c\dot{x} + kx = f$$

$m\ddot{x}$: Inertia force of mass point
$c\dot{x}$: Damping force of mass point
kx : Resistance force of mass point
f : External force (Seismic force)



1. Response spectrum method (Spectral Modal Method)
   Called the Mode Superposition Method or Modal Analysis, it is practical in that it can be manually calculated.
2. Time history response analysis method
   In order to analyze the dynamic response of a structure which receives irregular disturbances as in the case of earthquake ground motion, numerical integration is the most common technique for solving the equation of motion by integral calculus for each minute of time interval.
   There are
   - Time history mode analysis method and
   - Direct integral method
3. Frequency response analysis method
   The vibration system equation of motion calculated in frequency domain, thereby transforming response from the time domain to the frequency domain, and its reverse use of the fast Fourier transformation.

Further explanation of the analysis is omitted as it is too technical. It is suggested that you refer to a book dealing with this specialty if you are interested. The dynamic analysis method has dramatically developed in step with the advancement of computer technology and records of actual strong earthquake motion, but there are still numerous problems to be resolved and it can not be regarded as the most reliable method. A couple of examples of obstacles to be overcome in applying the dynamic design method are given here.

- Is modeling of the structure correct?
- Is the seismic wave to be input adequate from the viewpoint of the characteristics of location and structure?

  Regarding seismic waves, actual earthquake ground motion is extremely complex and irregular owing to a host of uncertain factors. Reappearance of a wave thus formed is unlikely in the same area. Accordingly, there still exists a problem in that design utilizing an actual past seismic wave will not necessarily provide full reliability. "The specification on road bridges" (Volume on antiseismic design) specifies singling out the most appropriate input earthquake among existing records of strong quakes, taking into consideration soil condition and dynamic behavior of the bridge. However, past records of strong earthquake ground motion, while increasing in number, are still not sufficient.

- Is the damping coefficient of the structure evaluated correctly?

  Amplification of the response acceleration of the designed structure to ground motion depends largely on the damping factor. The damping factor shall be defined by the characteristics of the structure in relation to appearance and mostly to friction factors.

6. Verification of Design

As explained above, various current design methods are not faultless. They are good neither for one thing nor for the other. Moreover, design methods to satisfy for all kinds of structures do not hardly exist. This means that the most adequate design methods vary in accordance with characteristics of the structures to be designed.

Therefore, designers, though a certain design method has been stipulated by decree or design standard, should always review which design method is most suitable for their projects.

"Specification on road bridges" (volume on antiseismic design) in Japan stipulates verifying the safety of the bridge by comparing maximum intensity of stress and maximum displacement obtained by dynamic analysis with allowable stress and allowable displacement which are designated for antiseismic design by the seismic coefficient method.

In order to put the verification of design into practice, particular tests–actually shaking the real structure or scale model on a vibration table which enables reproduction of earthquake ground motion–is very effective.

Shaking tables have been made, either governmental or private, for antiseismic tests at many facilities in Japan. Among these is a large shaking table (15m×15m) with a maximum load of 1,000ton, enabling excitation in both horizontal and vertical directions. This is widely used for antiseismic tests of nuclear power plants, high pressure gas manufacturing columns, steel towers, etc.

7. Safety Level

There are three seismic design methods: dynamic, quasi-dynamic and static. It is also important to set up criteria by which to evaluate safety in an earthquake or earthquake resistance for buildings and structures. Seismic design method of the Building Standard Law of Japan ,as mentioned before, is twofold: it is stipulated that buildings shall be designed to withstand and prevent damage from moderate earthquake ground motion, and that they shall be designed not to collapse or harm human lives during severe earthquake ground motion. The above mentioned design methods will determine data on the intensity of earthquake motion to be input and analyze the response of a building. Designed values of earthquake resistance, however, will be quite different depending on the strength of a building and its structural components being set in either the elasticity or the plastic region.

Seismic design methods now in operation in various countries can be classified as follows:

7.1. Allowable Stress Design

A design method to keep stress acting on each section of members below allowable stress of materials. Since materials are assumed to be elastic, this method is also called the elastic design method. There are a variety of viewpoints with respect to allowable stress. It may be divided into temporary and permanent stresses, or it may be regarded as equivalent to one third or one half of yield stress, or coincide with yield stress.

7.2. Ultimate Strength Design

A design method to ensure safety against damage by taking plastic deformation of materials into account. Generally accepted in many countries, the method assures safety against damage by making sure that the resistance strength of the structural components which has been determined allowing for plastic deformation of materials is above the load acting on the structural components. In the design work, safety factors are used as a substitute for uncertain factors such as the strength of materials.

Buildings of reinforced concrete construction react in an elastic way to minor earthquake ground motion. Subjected to major ground shaking, they sustain damage such as cracked columns and beams and yielding reinforcement steel, losing their rigidity. In the process their natural period becomes longer and longer gradually, and the damage progresses and escalates more seriously. Subjected to repeated loads due to occurrence of a quake, quakes or other kinds of forces such as strong winds, they suffer progressively more extensive damage.
In the case of a structure built in accordance with the design method sustaining progressive damage and plastic deformation, it is a really important and difficult problem how insurers assess the damage in any particular accident, for the damage reaches the plastic region repeatedly. To what extent do insurers recognize the accumulated damage as recoverable under an insurance policy while taking into account allowable plastic deformation approved by a designer in the course of design work? And what grounds will they give for it? It will be necessary for insurers to study how to put into practice a scientific and mathematical approach to such difficult problems. It is important for architects as well as insurers to determine quantitative degree of loss to structures which have been or might have been damaged by an earthquake. In addition to generally visual investigation by experienced staff, evaluation of loss based on scientific analysis may be introduced, of which insurers should be aware.

7.3. Limit State Design

This is a design method which was developed from Ultimate Strength Design. Namely,

- Ultimate limit state
- Serviceability limit state
- Fatigue limit state

This is a design method in which the probabilities of a structure or its elements reaching limit state are kept below the allowable limit, making allowances for a variety of uncertain factors at the time of design work. For assessment of safety of a structure, there are two methods: while one is to regard load and the strength of materials as determinate, the other is to consider estimated load and strength of materials as uncertain and view safety through the theory of probability. The former is a conventional design method, in which uncertainty and dispersion have been settled by selection of larger values with respect to load and by the strength of a material divided by the applicable safety factor. The latter is applied to the limit state design method or more accurately probability-based limit state design (PBLSD), which, adopting the concept of reliability design, attempts to determine these larger values and safety factors in a more reasonable way.

While there remain some problems to be resolved in this design method, which therefore has not yet been actualized in practice widely, a frame work for a quantitative analysis of uncertainty through suitable reliability analysis can also be adaptable to insurance underwriters as the method for the assessment of risks. We thus should pay attention to the development so as to see realization in practical use.

American Society of Civil Engineers (ASCE) "Standard of on Minimum Design Loads for Buildings and Other Structures," CSA Standard "Steel Structures for Buildings (Canada)" and New Zealand Standard NZS4203:1992 "Code of practice for General Structural Design and Design Loading for Building" adopted this type of design method. and of the latest the provisions of Part 4. Earthquake Provisions 4.2. General Requirement 4.2.2. Limit State reads as follows.

"All structures shall be designed to have

(a) Adequate strength and stiffness to satisfy the serviceability limit state, and

(b) Adequate strength, ductility and stiffness to satisfy the ultimate limit state."

Subject to the remarks by IAEE in the *World–List, NZS3101:1982 Code of Practice for the Design of Concrete Structure* is in ultimate strength for mat with serviceability checks, and is soon to be changed to *Limit States Design* format.

8. What is the objective of the safety level for the designer?

One of the problems that the Great Hanshin Earthquake revealed was the big gap between the performance level which the designer had in mind and the performance level that the building owner expected. There thus arises the strong proposition that the design and the construction should clarify the behavior of buildings, structures and facilities in a large earthquake to the purchaser.

The Ministry of Construction of Japan has undertaken research on building structure in an attempt to change her Building Standard Law and its ordinance from the specification code type to the performance code type. In the U.S., a study was started in 1992 by SEAOC (Structural Engineering Association of California) dealing with the performance code antiseismic design standard: VISION 2000.

A specification code type design method that defines, for instance, concrete specifications on the amount of reinforcement steel to be incorporated or on the diameter of the tie hoops holding the reinforcement steel restrict the latitude of the designer.

On the other hand, an antiseismic design method with a performance code clearly indicates antiseismic performance level, saying "no likelihood of collapse in an earthquake once in a 1,000 years," and accordingly leaves to the discretion of the designer the design specification once it satisfies the fixed performance level.

This turnabout may be of concern to the insurance industry in the future and will certainly bring various knotty problems to be solved. On the other hand, some may think that this trend will bring new business chances to the industry. In any case, with this turnabout, the need for performance guaranty insurance and liability insurance will concurrently emerge, which we should regard with serious concern.

Future design methods, such as the limited state design and ultimate strength design mentioned above, will increase the requirement of the insurers to obtain more technical as well as professional knowledge, while engineers in the insurance industry will be expected in the future to improve their ability and its fulfillment.

9. Problems involved in antiseismic design

9.1. Importance of subsoil conditions of surface ground

Subsoil is the critical factor for insurers in their assessment of earthquake risk. It is not too much to say that the characteristics of subsoil exert a decisive influence on the seismic hazards to structures. Earthquake ground motion--propagated from the seismic bedrock to the surface ground--is immensely amplified by the subsoil located on the bedrock. The deeper and softer the subsoil, the greater the amplification factor. The importance of subsoil was clearly apparent in the Great Hanshin Earthquake. For example, buildings located on an old dry riverbed collapsed, though in the city some buildings remained unharmed right next to buildings that collapsed. And some damaged sections of elevated bridges for the Tokaido super express trains were also on old dry riverbeds.

For the investigation of subsoil, but the best way is to refer to the report on soil research (boring data), which however is not done perfectly due to cost involved. I know of cases where insufficient boring data was available, but archaeologists could provide plenty of information in relation to the subsoil.

It would be helpful to realize that archaeologists are aware of what is buried in the subsoil and may be able to provide us with important information on historical locations.

Another reference pertaining to subsoil the example of the reclamation of two lakes in Mexico City. The following is quoted from a publication of the Munich Reinsurance Company (*Earthquake Mexico '85*).

"The soft sediments of the dried-up lake have a resonant vibration period of about 1–3 seconds at the sediment depths in the middle of the city. Accordingly, the subsoil is like a resonance amplifier for all earthquake waves of this frequency, which are thus intensified by a factor of 5–20. The peak accelerations measured were therefore 1 percent of gravity at the edge of the valley, 4 percent in the university area built on volcanic rock and up to 20 percent in the city center. Possibly, even these peaks were exceeded at certain points. With horizontal shifts being intensified accordingly, a large part of the city was shaken to and fro by 10–40 centimeters at intervals of 1–2 seconds for almost an entire minute."

9.2. Liquefaction phenomena

Since the Niigata Earthquake in 1964, the seriousness of damage from liquefaction has widely been recognized, and this has stimulated research on factors that cause liquefaction.

The Great Hanshin Earthquake reminds us again that the lateral flow of soil in reclaimed land can cause disastrous damage, in this case to port facilities and container cranes, in particular.

Since the Niigata Earthquake, the main effect of liquefaction has become clear to a considerable extent, by virtue of probes of the actual damage and through subsequent laboratory tests. While it has not become completely clear at the present time, the mechanism of liquefaction is by and large said to be as follows.

Volumetric shrinkage occurs when sandy soil composed of comparatively loose granules is shaken in the quake and the sand tends to be compacted. Dry sand will be compacted at this stage, but sand saturated with water will not immediately be compacted because of the water. Temporarily, granular sand will float in the water because the chain of contact between granules is broken by shear force. This is liquefaction of sand. As the pressure of the water increases in response to the pressure of the shaking, volumetric shrinkage occurs by shearing. It is said that the phenomena of boiling sand and the lateral flow of soil are created by this process. Another view is that while the sands are revolved by earthquake ground motion, a water film is formed among granules and the granules are disconnected by the water film.

Container cranes at the port of Kobe sustained heavy damage from liquefaction and the concurrent lateral flow of soil. But high-rise buildings (residences, hotels, offices), as naturally expected, did not suffer from direct damage from liquefaction though they were located on the same reclaimed land. If the current antiseismic design standard for the port–stricter than that at the time of construction and strong enough to cope with lateral flow of soil–had been applied, different damages would have been sustained. Increased pressure in reclaimed land due to liquefaction could not have found an outlet and pressure would have been released at a different location.

9.3. Sloshing

Sloshing in a tank is a typical example of the problem of long-period vibration at an earthquake. Insofar as the vibration of the tank itself is of concern, its natural period is not very long and is not different from the structures which are under study. The natural period of sloshing is sometimes longer than 10 seconds, particularly in a tubular type tank with a flat bottom. While this phenomenon was conspicuous in the Niigata Earthquake in 1964 and the Alaska Earthquake, this type of action has been known for a long time and actually was recorded in the case of the Great Kanto Earthquake. Occurrence in the Kern County Earthquake (U.S.) in 1952 prompted analytical study of this damage. Contrarily, one of the reasons that this damage was not regarded as a vital factor for a long time either in the U.S. or Japan was due to the input of earthquake ground motion for analysis. That is, El Centro–one of the earthquake ground motion inputs for antiseismic design standards in the U.S., Japan and other countries–was not considered to have had a long-period component. It is assumed that analysis using this wave would have resulted in the response component of sloshing being less than around 10 percent of the response component by input acceleration. Consequently, the conclusion drawn erroneously in numerous treatises was that it was not necessary to take sloshing into consideration in designing flat bottom tanks.

Damage caused by the sloshing phenomenon is not limited to flat bottom tanks such as outdoor oil tanks, etc. Inside the factory building, too, there are many container vessels for high temperature liquids, strong acids, alkalis, etc. Actually, the Great Hanshin Earthquake caused several incidents of spilling or overflow of vessels of high temperature melted aluminum for diecasting and melted solder. Fortunately, as it was early in the morning when the earthquake hit the factories, fewer workers were on the premises. If it had been during working hours, many bodily injuries would have been sustained.

Furthermore, we know of cases where very poisonous cyanogen spilled out of the electroplating bath at aircraft manufacturing factories, etc., caused by the sloshing effect of the earthquake. It is one of the most serious problems not only in relation to antiseismic design but to the environment problem. But unfortunately, I have not seen any information about effective design techniques to prevent sloshing damage from tanks, vessels, etc., except vibration isolation systems in a very limited area.

While recognizing that knowledge on long-period ground motion is abundant, data on large earthquakes and nearby epicenters are not sufficient and in fact the prediction of ground motion for design purposes faces tremendous challenges.

9.4. Vibration isolation and vibration control system

As a measure of the improvement in increasing the performance of antiseismic design, growing interest is seen in active vibration control systems and construction of vibration isolation, which are in fact being increasingly put to practical use. These are different from earlier methods of strengthening a structure. Their purpose is to reduce the earthquake ground motion entering a building or absorb earthquake energy mechanically. This method not only enables the antiseismic performance of the building to be improved but expands the dwelling space inside the building by virtue of the reduction of the cross section of the structural element. And it heightens the amenities of living through less shaking in an earthquake. Though we briefly mention this mechanism, we would like to put aside detailed illustration until a later time.

9.4.1. Vibration isolation system

The following are constructions for vibration isolation:

1. Isolation of equipment
   For precision instrument electron beam lithographic instrument, minification exposing projector
2. Isolation of whole floor of a room
   For computer room of bank
3. Isolation of whole building
   For residential flats

As regards the total building, by installing laminated rubber isolator, response acceleration of the building in an earthquake can be reduced to 1/3–1/5 that of a conventional building not having one.

9.4.2. Vibration control system

The vibration control system consists of a passive damper, which increase the damping effect of a structure by an oil damper or a friction damper, or an active damper which senses the response movement of a building to wind or earthquake and actuate counter movement of the building etc. by the computer to steady the vibration. The latter is adopted in high-rise buildings and enhances a comfortable living situation by eliminating unpleasant motion from wind or earthquakes.

10. Quality Control of Design Method and Workmanship

Will structures be built exactly to design? That is a question to be asked before applying a particular seismic design method.

It can be said that design earthquake ground motion and response of structures are almost always stipulated in laws and ordinances by governmental bodies, or independently specified in design standards set by nongovernmental organizations. Therefore, designers are accustomed to doing design work in accordance with established routines or an in-house manual based on them. Today computer-aided design (CAD) and manufacture (CAM) are often used to support of design work. In some cases, therefore, designers have no knowledge about the intermediate process of structural calculation. Such stipulations and standards make it easier for designers to carry out design work for structures and are instrumental in keeping workmanship at a certain level and reducing slight human errors.

However, it is feared that some errors in the process may be easily overlooked. That is why it is very important to verify design work. For instance, because of the difficulty in tracing the process of design calculation, it is impossible to find an error at a glance except in cases where the result is an unreasonable figure as a result of the calculation. Furthermore, if the result of calculation is accepted without full understanding of the calculation process, the defects or errors of input and output data are inevitably increased. To reduce these errors the “Japanese Concrete Bridges Design Manual” of the Japan Road Association advises structure designers to verify, to the extent possible, the entry of the input-output data into the design calculation sheet. Concurrently, along with clarification of the name of the applied program, JRA recommends that the main figures shall be examined tentatively in advance by ordinary calculation methods, particularly in the case of an unfamiliar program, thereby confirming the result of the calculation.

The question asked at the beginning of this chapter was, "Will structures be built exactly to design?" Further questions are: Does the quality of materials to be used for a structure, such as the steel and concrete, comply with the specifications as drawn up by the designer? Has work, such as pile-driving for foundations and welding, been carried out in accordance with specifications?

No matter what new theory a designer may apply in making an analysis for design work, antiseismic design will be meaningless, and the structure will be virtually a mass of rubbish, unless it is so constructed. It is no exaggeration to say that any design method will be insignificant to insurers unless design work, selection of materials and workmanship are properly examined. No failure to comply with the requirements ever became known and was pointed out before some major earthquake or storm. Such failure was often pointed out in investigative reports after disasters, although it was surely too late for insurers who had to pay for it, and few effective measures have been devised to deal with the problem.

The problems are widely recognized, effective measures remain undeveloped. Innocent loss should be avoided. Wouldn't it be advisable for the insurers to always leave the matter up to the discretion of others?

Oliver's Law states that experience is something you don't get until just after you need it.

11. Five-storied Pagodas

No five-storied pagodas have collapsed in an earthquake.

Lastly, reference is made to the technology of traditional Japanese wooden construction.

The year 538 AC saw the introduction of Buddhism from its cradle, India and China, via the Korean peninsula. The introduction of Buddhism simultaneously brought with it the Buddhist construction of China and Koguryo (ancient Korea) and has exercised great influence on Japanese architectural techniques. A great many temples were built with the pagoda being representative of numerous pagodas. The pagoda originated from the Indian stupa, which was built for the burial of skeletal remains, artifacts and ashes of the Buddha. The stupa preserves a vestige of the original finial or *sorin,* a bronze symbol, situated at the top of the pagoda.

Among ancient Japanese pagodas, there are three-, five-, seven- and nine-storied ones, the five-storied being the most common. They are all wooden structures and currently 200 old pagodas are preserved in Japan. In China the pagoda is mainly made of brick and those built of stone are prevalent on the Korean peninsula, there being only one wooden pagoda in each country. The oldest in Japan is the pagoda of the Horyuji temple, with a height of 32m, built in 719AC in Nara.

The second largest is the Higashi pagoda at the Yakushiji temple in Nara, which is three-storied with a height of 34m and was built in 730AC. The largest in Japan is the pagoda of the Kyogokokuji (Toji) temple in Kyoto, which has a height of 55m and was built in 1644.AC The reason for raising the topic of pagodas in this paper is that none of them have collapsed in an earthquake since the introduction of Buddhism in the 6th century. Other temple buildings have fallen in earthquakes, and many pagodas have been destroyed by fire. There are historical records of pagodas burnt in thunderstorms or war. In fact, quite a few pagodas must have experienced at least one or two earthquakes, maybe more than ten. Considering the riddle of the pagoda, one may be motivated to unravel it in the course of analysis of antiseismic and wind resistant design. In fact, some of the old ones have been maintained for over 1,200 years and most have been preserved for several hundred years in Japan, which is an earthquake and typhoon prone region.

Why haven't pagodas collapsed in earthquakes? This interesting riddle of antiseismic technology has been the subject of several hypotheses and deep interest among architects, particularly in the aftermath of the Great Hanshin Earthquake. There are many old wooden pagodas in the Kansai, the western part of Japan, among which thirty-one pagodas in Hyogo and Osaka were not damaged by this earthquake.

In our bid to contribute as much as possible to the research on antiseismic and wind resistant design and to provide a clue for those interested in untangling the mystery, we here give information on the traditional Japanese construction techniques of wooden pagodas.

11.1. How long in the lifetime of wood?

Ancient Japanese architecture can be seen as depending on the "culture of wood." Even now, Japanese love trees and wish to live in a house made of wood. To our regret, Japanese forestry, which once provided ample construction materials of good quality, is now unable to meet the demand and is dependent on importation. It should be noted that trees, even after they were cut down and made into timber, felt better being used at home than in foreign countries where climate and natural conditions are completely different, and could enjoy longer life as materials for architectural structures.

Moreover, people who really know trees are getting fewer. Luckily, some architects and shrine builders who exclusively engage in building shrines and temples with traditional architectural skills still survive and preserve the skills of especially traditional wood construction technology. According to them, the Japanese cypress is especially excellent for wood construction in all respects.

Though the common belief is that, once cut, Japanese cypress is dead and is nothing more than timber. On the contrary, it is said to live for more than 1,000 years, provided that it had lived for a 1,000 years before cutting.

Horyuji temple in Nara is said to be the oldest wooden structure in the world. The reason is said to be that the construction material was Japanese cypress, which actually preserved the strength of the temple for 1,300 years. Japanese wood culture slows the deterioration of wood for such a long period.

Japanese wood culture preserves the ruins of trees or the wooden materials for thousands years. Excavation and research of ruins and the repair of historical shrines and temples by dismantling can provide ample test materials of old timbers. Research by Dr. Jiro Kohara of the Chiba Institute of Technology, who tested this kind of timber, revealed that the life duration of Japanese cypress is more than 1,000 years. From ancient times, Japanese cryptomeria, pine and zelkova, most popular species of indigenous trees from ancient times, have been employed as construction material. The life time of Japanese cryptomeria is 800 years at longest and that of pine and zelkova is 400 years.

In short, according to Dr. Kohara the timber after cutting become stronger rather than weaker in accordance with the aging deterioration of cellulose and lignin, main ingredients of the tree. The Japanese cypress's intensity for bending and hardness gradually increases by 20% for 200 to 300 years after cutting, then returns to the original intensity after 1,200 years. There is a marked difference between needle-leafed trees and broad-leaved trees. The intensity of zelkova is about two times that of cypress as new timber but, owing to rapid deterioration, it becomes weaker than cypress after several hundred years. The deterioration of zelkova for 500 years corresponds to that of 100 years for cypress, the cause of which is the difference in resisting power for the aging deterioration of cellulose.

11.2. Structure of the five-storied pagoda

The five-storied pagoda is composed of a central pillar (called *Shinbashira*) sustaining its finial *Sorin* and a multistoried tower embracing the central pillar like a sword in its scabbard. The multistoried tower is composed of four inner columns (called *Shitenbashira*) and perimeter columns (called *Kawabashira*) around the central pillar. Each story of the tower is separate and independent. That is, the inner and perimeter columns sustaining the weight of the tower are discontinuous in each story other than the central pillar.

On these columns, there is a structure called *Kigumi*, combinations of timbers and complicated supports which prop up the eaves. In the process of construction, columns are loaded on this story and are continuously piled upward story by story till completion. The combination of timbers, composed of complicated and variously shaped wooden blocks, are firmly interlocked both vertically and horizontally, like a jigsaw puzzle in three dimensions. It should be noted that no metal materials such as nails, clamp irons or clasps, are used in these parts. No bonding agents are used, either. In fact, it is like a module flexibly combining each component. Though the central pillar goes through each story of the tower, it is not installed for the purpose of supporting the weight or propping up the pagoda. The central pillar's function is to sustain the heavy finial (*Sorin*) at the top of the pagoda, the most important part. The weight of the *Sorin* of the three-storied pagoda of Nara Yakushiji temple is 3.5 tons.

There are a number of ways of providing a foundation for the central pillar. The classic one, seen in the Horyuji temple, is to bury it in the ground. In the case of the Yakushiji temple, the central pillar is built so as to connect the central pivot and its hole on a stone foundation, which is called *Shinso*. Though the central pillar is connected to the uppermost roof of the highest story of tower, it never touches any part of the structure of the tower. The central pillar of the pagoda of Nikko Toshogu temple hangs by a chain from the upper beam of the fourth story and seems to be floating over the stone foundation. There is another example of a central pillar that is sustained by the first-story ceiling. From these facts, some maintain that the central pillar functions as a damping system at the time of an earthquake. Incidentally, the central pillar is only seen in Japan and Korea. Chinese pagodas are not equipped with a central pillar.

11.3. Response of five-storied pagodas to earthquakes

According to a observation made by Tsunekazu Nishioka, a temple carpenter who actually observed the shaking of the pagoda at the Nara Horyuji temple in an earthquake, "When the first story inclines to the right, the second story counteracts by leaning to the left and the third story shifts to the right alternative moves in opposite direction as if in the surge of a wave. The center of the pagoda never moves. The central pillar functions as an arrester of motion during a large earthquake."

What we now call flexible structure had already been created 1,300 years ago. Other than this fact, several results of scientific research or witness's remarks have been made public. The following are some of the views relevant to reasons why pagodas do not collapse in earthquakes.

1. The pagoda swings slowly, the natural period being mostly about 1 to 1.5 seconds. Some are 0.4 or 1.8 seconds.

2. The pagoda performs a snake dance. Under attack at any frequency range of earthquake motion, the phenomenon of head-shaking at the top floor is seen early, which tends to curb the movement of the next lower story.

3. Increasing a speed of disturbance motion creates fear of collapse but the central pillar collides with the floor of the fourth story, which prevents excessive movement of the pagoda and it is restored by itself. The lean of the pagoda at the time of collision is nominal and collapse of the pagoda itself is not likely.

4. The central pillar curbs the concentration of the displacement force at any story.

5. The central pillar is not effective for primary mode (linear mode) but will work effectively because the whipping movement of the head shall predominate in the case of the pagoda. During a typhoon too, when the pagoda is exposed to gusts of a duration of 5 to 10 seconds, active motion of the central pillar is seen to the extent that the upper part is twisted, according to one record.

6. Each story of the pagoda is built relatively separate and they act as a sort of damper on each other.

7. The weight of the finial is around 0.5% of the pagoda, and it may be said to function as an active damper like those recently installed at the top of modern high-rise buildings.

8. With the vibrations of the earthquake, the pagoda creaks because of the combination of wooden blocks and interconnected timbers, which gives rise to friction. Energy, devoted to transforming the pagoda, is consumed by that movement, i.e., the damping effect.

Dr. Kiyoshi Kanai, a seismologist, expressed the following viewpoint in his treatise, "On the Antiseismic Nature Of the Five-storied Pagoda." "The antiseismic nature of the five-storied pagoda may be construed as coming from the interaction and friction of the combination of timbers and blocks , which swiftly increases as the vibration becomes intense. The cause of increase in the friction force may lie in the fact that the principal axis of the locus of motion at the upper part of the pagoda during on earthquake is directed in a diagonal line." In other words, he states, "The pagoda probably becomes a unitary construction with the increased friction in a strong earthquake, and there are no records of collapse. This is to be interpreted as scale effect."

Among the various examples, a definite conclusion has not been drawn as yet. Hopefully, research and study with up-to-date know-how will sooner or later unravel the truth. In the contest of wits between architects of 1,300 years ago and those of our own day, can the present-day architect untangle the long standing mystery of architectural field?

12. Wind Resistant Design

Due mainly to focusing on the issue of earthquakes, this paper has not taken up the matter of wind resistant design. In actual fact, buildings will be more strongly affected by wind than by earthquakes should the natural period get longer than around six seconds. Specifically, the design of many technical issues of the design method for long-span suspension bridges and super high-rise buildings, which is of profound interest for our study, will regretfully have to be postponed to a later time.

13. Afterword

In completing this research paper, we have received enormous support from IMIA members. Very important information has been given in the questionnaire returned to us. IMIA members, professors, construction people, manufacturing and insurance companies have been generous in providing us with necessary advice and information to an extent greater than expected, all of which has been helpful to us. We would like to extend our deepest gratitude to all of them. Because of the Great Hanshin Earthquake since last year book stores have been filled with publications on it, which has added to our sources of information. Participation in several academic seminars has helped deepen our knowledge as well. In the process, mountains of materials and information that have remain untouched on book shelves include materials on the wind resistant design of the Akashi Strait Bridge (now under construction) and of damage in Typhoon 19 in 1991, together with related information.

We will strive to sort out these precious materials, but owing to limited space, we are having difficulty in selecting materials, and your understanding is appreciated. For us, it was the first occasion to approach the issue in this way and thus we tried to put forth the matter rather extensively. As a result, we frankly acknowledge that this paper is less than perfectly organized, but we will feel very fortunate if it stimulates your interest in the subject and eventually contributes to your subsequent discussions.

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