EARTHQUAKE RESISTANCE OF TRADITIONAL JAPANESE WOODEN STRUCTURES

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Now that this big event of the Second World Conference on Earthquake Engineering is coming to the end today, I would like to take the opportunity to express our sincere hope that all of you, especially those who are participating in the Conference from abroad, will spend several days from today in seeing or sightseeing JAPAN.

Until the end of last century, Japan was a country almost isolated from all over the world, and, only through the gate of Nagasaki, a harbor open to Dutch missions alone, Japan got a glimpse of the Western civilization. Therefore, Japanese culture --- costumes, foods, houses or architecture, painting, music, literature and so forth --- has on the whole been uniquely developed and refined, although it was said that seeds of Japanese culture were brought from ancient China.

Also, the city of Kyoto was the metropolis of this country as well as the center of Japanese culture for one thousand years until Japan has begun widely to appreciate the modern Western civilization. Hence, every aspect of the culture has been so well preserved that it can be seen now in and around Kyoto city. I think therefore that Kyoto, the site of the Closing Session for this Conference, is a right place in order to introduce you the uniqueness of the Japanese culture.

As for Japanese architecture, too, it has been accomplished in its own way, so that you might be interested in the background of the development of the Japanese architecture with distinctive features. The Japanese architecture was of wooden construction. As you can see, the prevalence of the construction and the development may be due to the fact that a large portion of the land of Japan is mountainous, being covered with beautiful forests of the flora in the humid and temperate zone --- Japanese cypress, Japanese ceder or pine --- and therefore that this country is rich in fine structural timber.

The most striking feature of Japanese wooden structures may be seen in the deep overhang of eaves of the houses. For the purpose of preventing the structural members from decay or corrosion, it has been necessary in this rainy land to have such a deep eave for every

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building. The technique of the wooden construction capable of carrying the long overhang had been developed in the mainland of China, and it was brought through Korea to this country in the 7th century, when a number of temples were dedicated by utilizing this technique. And an example of these temple buildings can be seen in Horyu-ji Temple in Nara, which has been almost perfectly preserved and is thought of as the oldest wooden structure in the world.

In the 8th century, the continent of China had the most refined culture ever attained in the world at that time. This style of the Chinese architecture was also brought into Japan, and you can see now in Nara the fine examples of the temples dedicated in that century, all of which have superiority in the sense of structure and art.

I suppose that some of you from abroad may have already seen a number of pagodas or towers of Japanese temples. Here in Kyoto, we have a three-storied pagoda in Kiyomizu-dera Temple, five-storied pagodas in Yasaka and To-ji Temple, and so on. All of them were beautifully constructed late in the 14th or 15th century. I regret that at present you cannot see the five-storied pagoda of To-ji Temple because it is under construction for repairs, but the pagoda is about 180 feet high and may be counted as one of the world's tallest wooden structures.

As I have mentioned, there are many ancient wooden pagodas in several places of the country, but it may rather be striking to note that there have ever been reported no earthquake damages to the pagodas. Therefore, it will be very appropriate to speak of the pagodas as the main topic of my speech today.

The earthquake-resistance of the wooden pagodas has, of course, been an interesting problem of study for seismologists and engineers in this country, and essays of the many investigators on this subject have made as a whole a great deal of contributions toward the progress of earthquake engineering.

Back in 1927, I remember that an important dispute was made on the question whether an earthquake-resistant structure should be rigid or flexible. The so-called "rigid structure" theory was first proposed by late Dr. Riki Sano who was one of the leaders in the field of architectural engineering in Japan, while the "flexible structure" theory was advocated by late Dr. Kenzaburo Majima, a Japanese civil engineer. (Refs. (1), (2) and (3)).

The theory of rigid structures of Dr. Sano states that, in order to be safe from earthquake, structures should have sufficient stiffness to withstand the lateral force of earthquake. This theory itself seems to be unanimously agreeable. However, Dr. Majima maintained that as a result of providing a structure with ample stiffness the structure would be rigid and then the action of ground motions would increase so that a more stiffness would be required for the increase in the earthquake action, since the seismic action is larger as the structure becomes more rigid. He therefore concluded that if we can make the structures being more flexible the seismic action on them would be much weaker and the structures would still be safe.

So as to illustrate his theory, Dr. Majima refered the five-storied wooden pagodas which are considerably flexible and have long natural periods of vibration. I think that this theory can be said an excellent notion in earthquake engineering, in which Dr. Majima has already taken the dynamic action of seismic waves into consideration.

A field survey has shown that the natural period of vibration of a five-storied pagoda was about 1.3 sec. In general, the natural periods of such pagodas are ranging from 1 to 1.5 sec or so. On the other hand, in the event of 1923 Tokyo earthquake, a seismograph record has indicated a little more than 1 sec period for the observed ground displacement.

Hence, as long as the periods are concerned, we may not say that the five-storied pagodas are the structure with the natural period long enough not to show any response to the seismic motions. However, since it is true that such pagodas have never suffered any serious damage due to past earthquakes, there must be an explicit reasoning necessary to prove the fact.

Accordingly, the following deduction has first been given to this. That is to say, a five-storied pagoda has a central column, which is independent from the surrounding structural frames, and is suspended like a pendulum from the top of the pagoda. Consequently, the pagoda is a peculiar type of structure having a pendulum and thus it may be earthquake-resistant.

This deduction seems to be very interesting. However, the technique of the suspended column has been contrived in about the 17th century in compliance with a demand of eliminating the difference between shrinkage of the central column and the surrounding frames. The shrinkage causes deterioration or failure of roofs of the pagoda. Moreover, there are many examples of pagodas in which the central column stands directly from the ground level, and in some cases of three-storied pagodas, the column stands on the second floor (Fig. 4). This will be clear when you see the model of a three-storied pagoda that is one of the exhibitions in the lobby.

Consequently, the deduction, assuming that the earthquake-resistance of a pagoda is entirely by virtue of its central column suspended like a pendulum, could not tell the truth.

Dr. Taniguchi has given a reasoning for the earthquake-resistance of pagodas (4). According to my remembrance, his explanation can be summarized as follows. During an earthquake, the central coulmn in a pagoda usually vibrates in the modes of flexural oscillation like a cantilever beam, while for the surrounding frames we can assume a dynamic deflection curves similar to those for shear beams. Hence, the two different types of vibration modes for the column and the surrounding structure may constrain each other to reduce considerably the overall deformation of the pagoda.

Late Dr. Sezawa has made a calculation to estimate the static stiffness as well as the yielding range of five-storied pagodas for lateral loading and was convinced that the earthquake-resistance of the pagodas might be attributed to its large strength against a lateral force, (5), (6) and (7).

On the other hand, Dr. Muto has paid his attention to the damping capacity in such pagodas which is also concerned with the earthquake-resistance of the structures (8), while from an experiment on a half-size model of the main hall at Horyu-ji Temple Dr. Ban has pointed out that the traditional Japanese wooden structures show in general a large magnitude of deformation up to their collapse (9).

As I have mentioned, the five-storied pagoda has brought in many interesting subjects of study in earthquake engineering. Now, let us abstract a number of leading facts being stated in those reasonings or hypotheses by the scholars. These are:

1. The natural period of vibration of the pagodas is generally long, and in most cases it is more than 1 sec. However it may, or not, be compared with the period of ground motions, the natural period is very long in comparison with those of other types of structures.

2. The pagodas are not so weak structures but they can withstand considerably large lateral loads.

3. The pagodas have a large deformation limit up to their complete failure.

4. The pagodas can be expected to have a pretty large amount of structural damping.

Namely, what I would like to say here is that the above four striking features themselves are the ideal conditions necessary for the safety of structures against earthquakes, and that the pagodas are the ones which satisfactorily fulfil these conditions.

Our intuition would sometimes lead us to think that the pagodas or towers will be in most danger of earthquake. But I can say that the intuition is a wrong analogy. Indeed, people are easily inclined to presume that the tall and slender pagodas will not be safe if they are subjected to a violent earthquake motion, since bottles or tombstones in the same proportion as the pagodas wholly drop like a log at every earthquake. However, I may say that people have failed to notice an important point which is the problem of size or scale, namely, the scale effect.

If the action of seismic waves may be assumed as a static force of constant magnitude, the effect of the earthquake will be equivalently the same for any size of structures. However, this is not the case, and since the ground motion is a complicated function of time, the problem of the size of a structure comes in.

In other words, if the action of an earthquake may be represented by a lateral force to act statically upon a rigid body at its center of gravity, the resultant of the lateral and gravitational forces is as shown in Fig. 1. Then, we may say that the rigid body would fall down regardless of the dimensions of the body whenever the horizontal acceleration of the ground motion exceeds a definite ratio to the acceleration of gravity. But the seismic action is not such a continuous, static one.

As shown in Fig. 2, the amount of kinetic energy necessary to bring the rigid body up to the position, where it is critical whether or not the body will fall down, is proportional to the linear dimension of the body.

Hence, it has become clear that our intuitive point of view that during an earthquake a pagoda would be equally unstable just as bottles or tombstones is nothing but an analogy mistaken by not taking the scale effect into account. The phenomenon seems to be similar to that of billows or surges which would overthrow tiny boats but do nothing for large cruising vessels.

The action of earthquakes or ground pulses on structures should be considered to have two important factors; one is the inertia force attributed to the acceleration of a ground pulse and the other is the duration of the pulse. The product of the ground acceleration and the time of duration contributes the velocity of the ground motion, and it will be illustrated later that the velocity is the measure of destructiveness of the earthquake.

If we express this idea in terms of scientific terminology, the mass of a body times the square of the ground velocity is associated with the kinetic energy given to the body by the ground motion. Therefore, the criterion to see whether the body is safely withstandable or not is given by a comparison of the kinetic energy and the potential energy stored up to the instant of fall-down or collapse of the body.

Consequently, on the safety of structures against earthquakes, we must note that the safety does inherently depend not only upon the measure of the strength of structures in the lateral direction but also upon an important characteristic that a large amount of deformation is possible. A high strength and a large limit of deformation of a structure give the structure a large amount of potential energy.

The dispute between Drs. Sano and Majima, that I mentioned before, was made because one has based on the measure of strength and the other had laid an emphasis on the measure of deformation. While the dispute was repeated for sometime as both of them were important criteria for the earthquake-resistance of structures, respectively, another different stand point to synthesize both of them was expressed in my theory of "Ground Velocity and Potential Energy of Structures".

Basing upon this stand-point, let us study again the earthquake-resistance of pagodas. The fact that a pagoda has a considerable lateral strength and a large limit of lateral deflection will indicate that a large amount of potential energy can be stored so that the safety of pagodas against earthquake is satisfactorily high.

I have spoken of damping capacity in pagodas which may be credited as one of the reasons why pagodas are earthquake-resistant. The pagodas are regarded as capable of undergoing a large amount of plastic deformation or plastic drift due to the specific characteristic of structural material as well as of the composite construction. This important feature of large plastic deformation is the main source of damping which effects the building vibration toward smaller amplitudes. And this was what I have already pointed out frequently (10).

As you will see the model of pagodas or other types of buildings, the traditional Japanese architecture has a capital on each column which is a composite wooden block necessary to carry the deep overhang of the roof (Figs. 3, 4 and 5). The composite block consists of timbers laid in piles. Namely, the timbers are placed horizontally and the load is applied in the direction perpendicular to the fiber of the timbers. During an earthquake, the distribution of the load may be influenced to some extent, and in case of such loading a great deal of plastic deformation occurs but the timbers will not break. Therefore, the composite wooden block on each column may absorb a large amount of vibration energy in the structure so that the pagodas are considered as a highly earthquake-resistant structure.

I have refered before about the natural period of vibration of the pagodas and mentioned that the longer periods of pagodas in comparison with those of other structures is very desirable for the earthquake-resistance of the pagodas. Now, I will take the problem to discuss it further.

The facts that the natural period of vibration of the pagodas ranges from about 1 to 1.5 sec and that the ground displacement-time record of the 1923 Tokyo earthquake had a period of about 1 sec seem to convince us that the pagodas are not so favorite structures as they will possibly resonate with the seismic waves.

A number of years later since the 1923 Tokyo earthquake, late Dr. Ishimoto of the Earthquake Research Institute of Tokyo University devised an accelerograph and subsequently a series of observations of earthquake ground motions have been carried out by using the accelerograph, and it has been made clear that ground motions usually consist of a series of acceleration pulses with far shorter periods than those observed by using the displacement seismometers (11), (12), (13) and (14). The results of observations have shown that the ground acceleration had periods ranging from 0.3 to 0.6 sec.

If we compare the natural periods of pagodas with the periods ground acceleration, it would be apparent that the periods of pagodas are far longer than the periods of the ground acceleration, and therefore that the pagodas have less possibility of resonance with such ground acceleration waves.

Moreover, using the accelerograph, Dr. Ishimoto has made a comparative studies of ground motion observations in Tokyo for an upland area or heights on diluvium strata and for the downtown on alluvium layers, and it was found out that in the upland area a predominant period of about 0.3 sec was remarkable while in the downtown a longer period of about 0.6 sec was predominant. And, from the view-point of resonance of structures with the ground motions, he gave the following explanation that flexible, Japanese style buildings were seriously damaged if they were on the diluvium ground and damage to rigid structures like masonry construction of brick or stone was larger when the structures were on the alluvium ground.

Of course, since the ground excitation is irregular and is far from harmonic, the resonance phenomena as observed in the mechanical vibrations do not exist. But, as stated in my paper submitted to the First World Conference on Earthquake Engineering held in 1956 at Berkeley, California, (15), even in case if we take into consideration a small number of ground pulses which are essential in an earthquake, it has been concluded that the effect of the ground excitation on a structure is most remarkable when the period of the ground pulses is nearly equal to the fundamental period of vibration of the structure.

Let us turn now to the discussion on the relationship between the earthquake response of the pagodas and the foundation. Old temples at which these pagodas were dedicated were generally built on strata of the diluvium or on the more solid ground generated in much older eras. On these solid foundations, the periods of earthquake ground motions are usually observed to be very short. This fact may also be favorable for the safety of the pagodas against earthquakes.

As for the ordinary residential houses in this country, they have been developed under little influence of Chinese culture. Although they had based on the technique of wooden construction brought from China, they were uniquely refined to fit very well the customs of living of Japanese people.

Just as the dynamic characteristic of pagodas is a desirable one for the earthquake-resistance even though the pagodas were built without such specific demands or any special schemes to make them earthquake-proof, the same thing may be said for the case of the residential houses in Japan. Namely, the reason is that they are all wooden structures with such materials and construction which enable the structures withstand safely a large amount of deformation.

According to the results of an experiment (16) by Dr. Saida of the Earthquake Research Institute, Tokyo University, which was carried out on a full-scale, single-storied, wooden building model, it has been shown that collapse of the model did not occur until the deflection of vertical-resisting elements due to the lateral load in the plane of walls reaches up to 17.5 centimeters per meter of height of the elements. This does indicate how large plastic deformation can be durable by the Japanese wooden structures.

However, a large part of the lateral strength of Japanese wooden structures is always attributed by the walls of soil. Hence, when the lateral strength of the walls is small the total potential energy is not enough to furnish reliable earthquake-resistance of the structures.

Therefore, it can be said that a guiding principle to utilize bracing members in the walls of Japanese style buildings, proposed by Drs. Uchida and Sano, is the most appropriate and effective means for the safety of structures. The "flexible structure" theory of Dr. Majima itself was a valuable theory but it might have less significance at that time for the purpose of increasing the reliability of Japanese wooden houses against earthquakes.

The wooden structures equipped with bracing members were found to be very earthquake-proof. For example, in the event of the Tottori earthquake in 1953, it has been observed that many old Japanese style houses were seriously destroyed while very little damage was reported for the buildings constructed on the basis of the guiding principle. Moreover, we can say that since many cities in Japan are located in alluvium areas the principle is very reasonable because it aims to establish high strength and rigidity of wooden structures to lateral loads.

In 1934, I had an opportunity of visiting Formosa, which was a Japanese territory at that time, to inspect damage of building structures resulted from an earthquake in the city of Taichu. I have observed there that brick buildings in a whole village were completely destructed to change into a pile of trash. On the contrary, many Japanese style wooden houses were sound though some partial failures or distortions were more or less noticed.

The Japanese wooden structure itself is substantially earthquake-proof because the structure is characterized to be ductile and elasto-plastic by virtue of the material and the way of composition of the structural members. It is no doubt, therefore, that wooden structure will be one of the most earthquake-resistant type of structures now and in the future if a more reasonable device or caution will be added from the achievements of earthquake engineering.

The common wish and hearty desire of all the earthquake engineers are to protect human being from miserable devastation of earthquake, or to prevent a loss of life of people from the earthquakes. In other words, this would be the same thing as to say that we should allow no collapse or complete failure of building structures even in the event of violent earthquakes.

This purpose will be accomplished when a higher safety of structures against earthquakes is secured by utilizing reliable, so that ductile, structural materials capable of increasing the potential energy which the structure can store up to the collapse. In this sense, we realize that it is a drastic measure of our pioneers in this field to have set up an article in the Japanese building codes, which is almost prohibiting the wide application of masonry structures of brick or stone.

The economical basis of estimation of building damages due to an earthquake will be able to rely upon the probability of occurence of a destructive earthquake at a certain area, the compensation for the damages will be able to be made by setting up an insurance system in a world-wide scale, if desirable. However, the loss of life cannot be compensated by any means. Hence, the most important problem of the today's earthquake engineering must be to study on a reliable device of preventing structures from collapse due to earthquake and to practice it.

This year, we have observed a serious earthquake damage in Morocco, and recently in Chile. I have seen the damages in movie news and noticed that there are still some buildings which any how survived without remarkable failure. This is not a miracle, but there must be the reason why these buildings survived in such areas under such a violent earthquake excitation. It is, therefore, very worthwhile for earthquake engineers to investigate or inspect on the survived building structures so as to establish a measure of destructive power of the earthquake.

After the events of Tottori and Fukui earthquakes, I have made a survey on the buildings survived from the earthquakes, and realized that this survey has given very valuable data.

For earthquake engineers, the event of an earthquake can also be considered as a very expensive experiment carried out by the nature. Hence, it is greatly desired for earthquake engineers to make a comprehensive survey on the results of the earthquake and to present the data which will be highly valuable for the progress of earthquake engineering.

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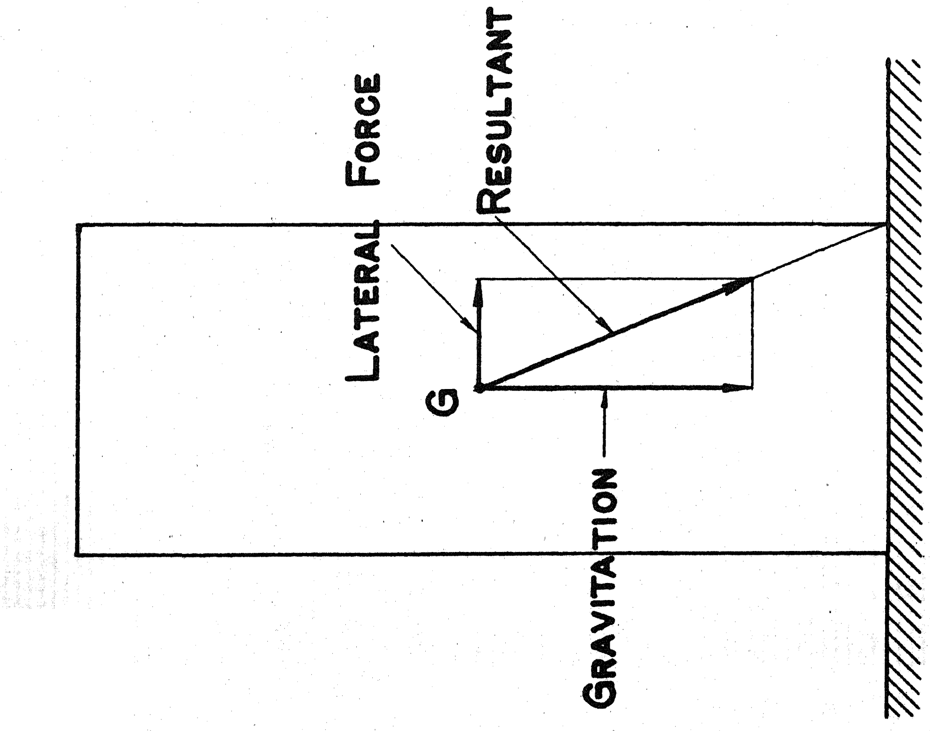

FIG. 1

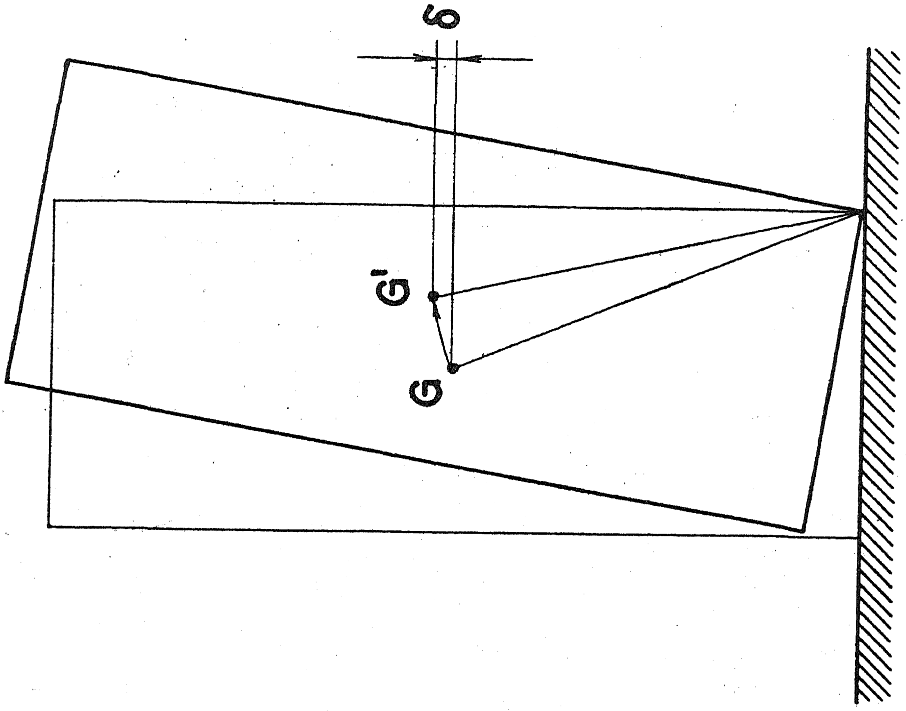

FIG. 2

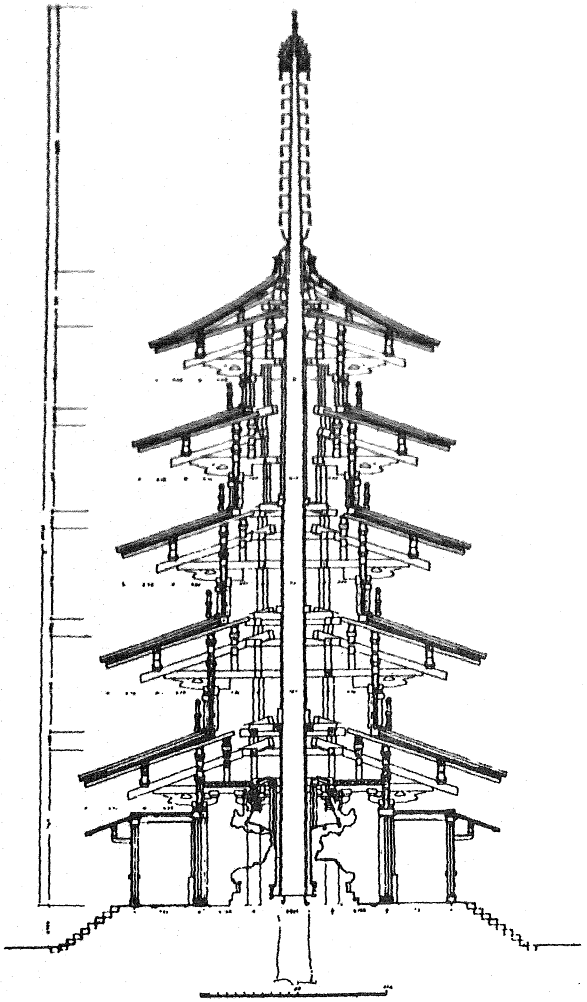

Fig. 3 Section of the five-storied pagoda at Horyu-ji Temple, Nara.

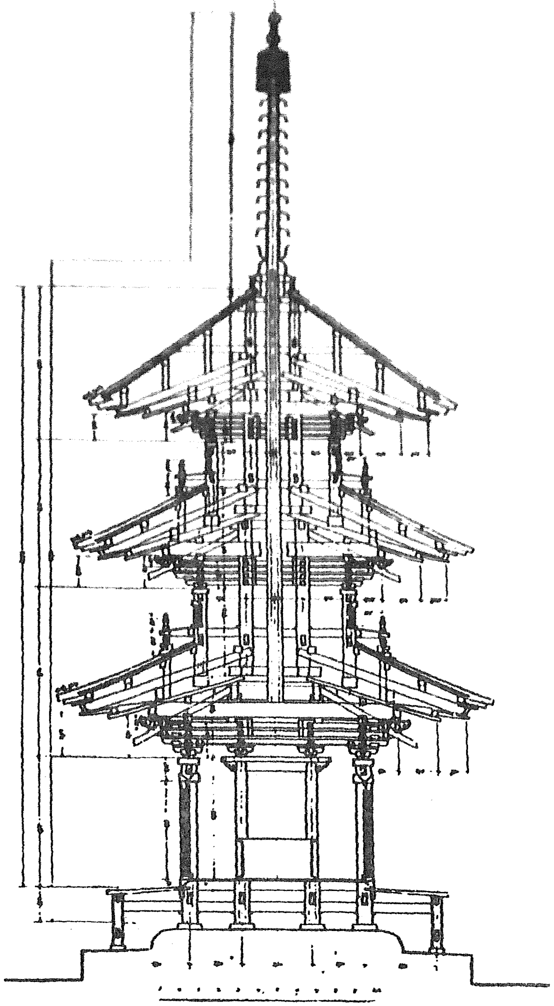

Fig. 4 Section of the three-storied pagoda at Sammyo-ji Temple, Toyokawa-shi, Aichi.

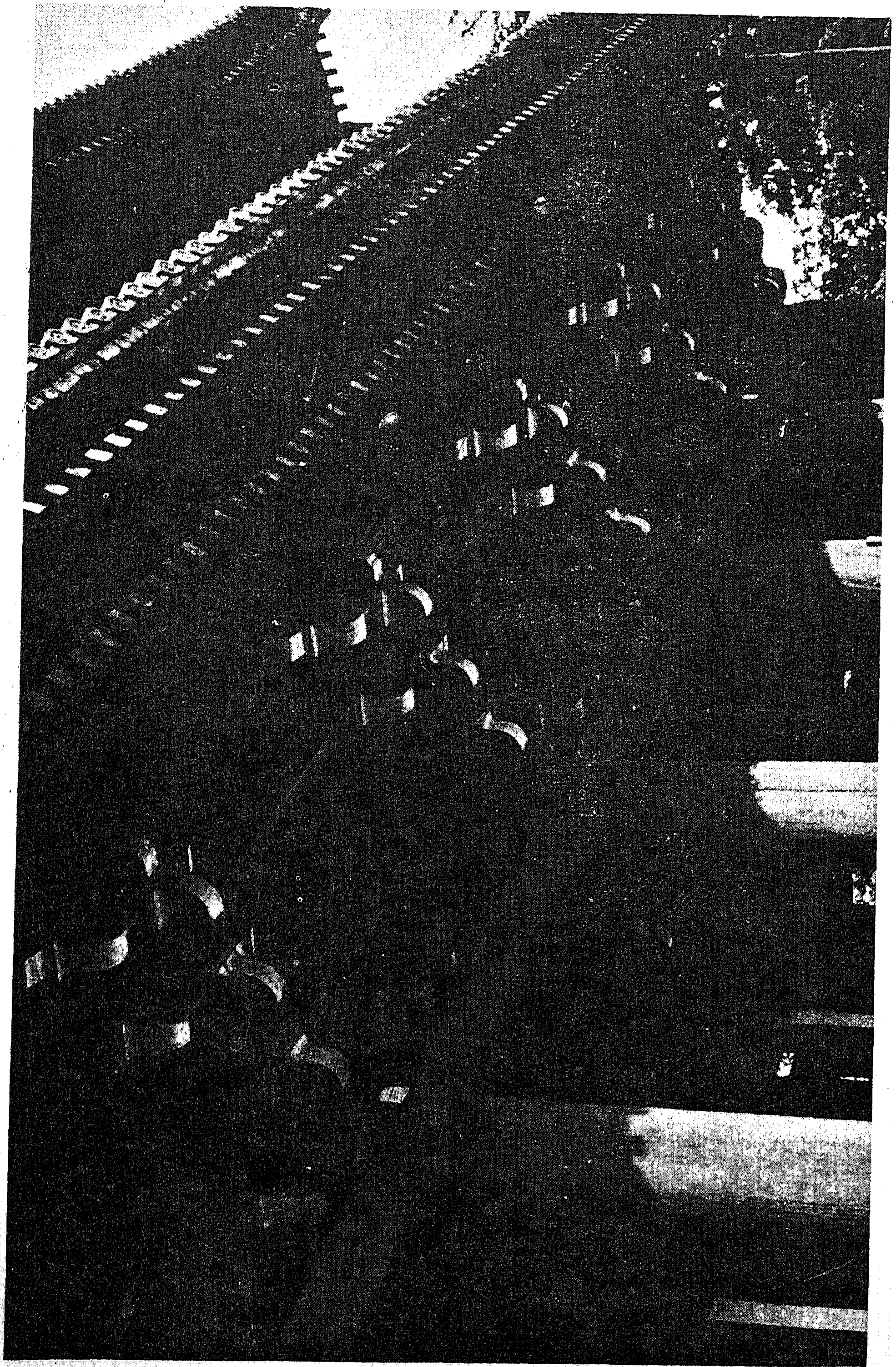

Fig. 5 View of the gate at Tofuku-ji Temple, Kyoto.