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STRUCTURAL CHARACTERISTICS OF WOODEN FIVE STORIED BUDDHISM TEMPLE PAGODAS AND APPLICATION TO THE MODERN ARCHITECTURE IN JAPAN

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Definition of Five Storied Pagoda: A five-storied pagoda is a symbolic tomb of Buddha. When Buddhism was introduced into Japan in 538, a five-storied pagoda became one of the important components of temple complexes. Present Situations of Wooden Five-storied Pagoda: There are 22 wooden five-storied pagodas in Japan. The oldest is the one in Horyuji Temple built in 710. The tallest is the one in Toji Temple with the height of 54.8 m. The shortest is the one in Murooji Temple with height of 16 m. Structural Characteristics: There is no historical record that five-storied pagoda was destroyed by an earthquake. A contributory factor is that no nail is used but carved holes or grooves in each of wooden pieces interdigitate precisely to form a structure. Another key factor is "A Central column (Shin-bashira)", an important wooden structural component almost 30 m long. There was no theoretical principle. A Central column is effective against an earthquake and it has been regarded to absorb the earthquake energy. Thirdly, five-storied pagoda interior space is effective to control structural deformation and shake of pagoda. The first theoretical analysis was done by 1/5 scale model in 2006 that proved the role of "Central column". Application to the Modern Technology: There are two cases presently. One is Marubiru Office building 178.5 m high built in 2002 and another is Tokyo Sky Tree, a telecommunication tower 634 m high built in 2012. Those structural design was influenced by a pagoda's central column as a vibration damping tool.

Keywords: Central column, Shin-bashira, Buddhism temple, Earthquake proof flexible structure, Vibration damping tool.

1 PURPOSE OF THE PAPER

The purpose of this paper is to introduce structural characteristics of earthquake proof five storied pagodas and two cases of modern architecture where traditional technology is applied.

2 DESIGN CHARACTERISTICS OF 22 WOODEN FIVE-STORIED PAGODAS

There are 22 wooden five storied pagodas built before the Meiji Period (1868) in Japan. 9 are designated as "National Treasure", and 13 are designated as "Important Cultural Treasure". There is no record that a five storied pagoda was destroyed by an earthquake in spite of occasional earthquakes in Japan.

2.1 The Oldest Pagoda, Horyuji Temple, Nara Prefecture

The oldest pagoda is Horyuji Temple Pagoda with the height of 31.5 m built in 710 in Nara Prefecture, an ancient capital. Those complex consists of the oldest wooden buildings, registered as a World Heritage Site. The width of the first floor is 6.42 m. (Fig.1)

2.2 The Tallest Pagoda, Toji Temple, Kyoto Prefecture

The tallest pagoda is Toji Temple Pagoda in Kyoto City, built in 1644 with the height of 54.8 m. The width of the first floor is 9.48 m.

2.3 The Shortest Pagoda, Murooji Temple, Nara Prefecture

The smallest pagoda is Murooji Temple Pagoda in Nara Prefecture built in early 800s with the height of 16 m. The width of the first floor is 2.45 m. (Fig.1)

2.4 Spatial Characteristics

The first floor is the place for the Buddha's bone case. Space between the second floor and fifth floor is regarded as a loft. The plan is a square shape of three-span structure, there are twelve columns along the outer wall line and there are four columns inside. A Central column is erected in the center.

2.5 Elevation

The proportion of a main part height to a total height of the Horyu-ji Temple of the year 710 is 0.701. It is 0.717 for the Muroo-ji Temple of the year 800, 0.730 for the Myo-oin Temple of year 1348, and 0.730 for the Honmonji Temple of the year 1607. The proportion of main part increased from the early period to the later period. (Fig.1)

The proportion of a main part height to a width of 1st floor of the Horyuji is 3.57. It is 4.73 for the Murooji, and 4.65 for the Honmonji. The proportion of a width of the fifth floor to that of the first floor of the Horyuji is 0.503. It is 0.594 for the Muooji, and 0.675 for the Honmonnji. Horyuji Temple, built in 710, looks stable and Honmonji Temple, built in 1607, looks slender. It is getting slender in later periods.

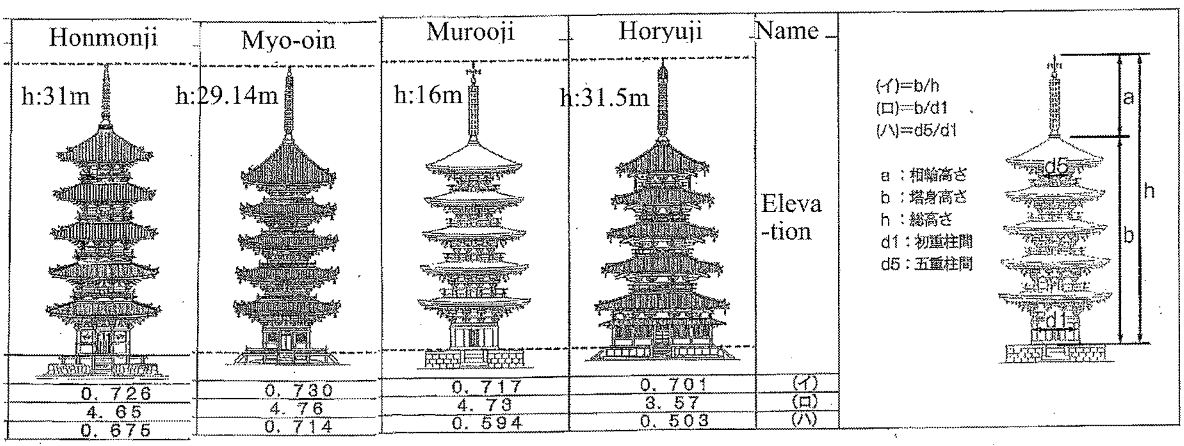

Figure 1. Proportion of Five Storied Pagodas.

2.6 Structural Features

Structural feature of a pagoda is a Shin-bashira erected in the center supposedly playing a role of earthquake proof. "The weight of a wooden pagoda is about 150 tons, there are 750 types of wooden parts, and 18,800 wooden parts, based on a recent case of a wooden five storied pagoda" (Hamashima and Sakamoto 2010).

3 STRUCTURAL CHARACTERISTICS -EARTHQUAKE PROOF

The five storied pagoda is an earthquake proof with a flexible structural system. Theoretical analysis have been done recently, but reality has not been found yet. There are a few theories of an earthquake proof structure of a pagoda.

3.1 Prof. Ohmori's Theory

In 1910, Prof. Fusakichi Ohmori did a research of vibration measurement in the Horyuji Temple to find that Central column has a role to control a shake of a pagoda. He pointed out "A Central column is an important key factor" like a pendulum (Hamashima and Sakamoto 2010). There was no theoretical principle then, but empirical principles by master carpenters. A central column is effective against an earthquake. Its pendulum isolation has been regarded to absorb the earthquake energy. Composition of each wooden part has high ability to absorb earthquake energy.

3.2 Prof. Riki Sano's Theory

In 1916, Prof. Sano reported that "resonance will not always occur, because five storied pagoda is tall, the natural period is longer especially, in case that the ground is solid, it is longer than the predominant period" (Hamashima and Sakamoto 2010).

3.3 Prof. Makoto Tanahashi's Theory

In 1960's, Prof Tanahashi reported in the Second World Earthquake Engineering Conference as follows,

(1) A pagoda shakes very slowly compared with an ordinary building. The natural period of a pagoda is between 1 and 1.5 seconds).

(2) The amount of wooden materials per square meter is so large that a structure resistance force is large against horizontal force.

(3) It resists against transformation (distortion) force, because there is very little space among many wooden parts.

(4) Composition of many wooden parts decreases earthquake vibration.

(5) A central column plays a role like a pendulum.

3.4 Prof. Kiyoshi Muto's Theory

In 1960's Prof. Kiyoshi Muto did experimental researches using model and reported that transformation performance is large in a pagoda.

(1) Small wooden parts absorb earthquake energy

Because of many wooden parts, a pagoda has a character of damping. Contributory factor is that no nails is used but carved holes or grooves in each of wooden pieces interdigitate precisely to form a structure. Each part will move little by little.

(2) Because of big columns, a pagoda has stability.

(3) Each floor of a five storied pagoda shakes in different direction.

(4) A five storied pagoda's interior space is not used for daily activities so that its structure is effective to control structural deformation and shake of a pagoda.

(5) Because of 17 columns including Central column, a number of columns is enough for its floor area (Hamashima and Sakamoto 2010).

3.5 Recent Research

Wooden Architecture Forum and Research Institute of Disaster Science Engineering executed the first theoretical research of structural behavior analysis of earthquake vibration using a 1/5 scale precise model of the Asuka Period wooden pagoda (592 till 710) from 2004 till 2008. The input data of earthquake energy is the same as the Hanshin Awaji Great Earthquake in 1995. Its magnitude is 7.3, maximum acceleration is 848 Gal, and maximum speed is 105 kine. The results are as follows:

(1) "It curves and its distortion of the second floor is s maximum point. (Fig.2)

(2) Maximum value of deformation is 1/33 radian, but there is no serious damage of test pieces.

(3) Composition of wooden parts has a much ability of damping.

(4) Central column has effects to control distortion and shake, but it does not enough contribute enough against earthquake proof."(Hamashima and Sakamoto 2010).

(5) But theoretical outputs on Central column structural features are not clear yet.

4 APPLICATION TO THE MODERN TECHNOLOGY

At present, there are two cases in which concept of Central column is applied, although design and planning are entirely different from an original five storied pagoda.

4.1 The Tokyo Sky Tree

The Tokyo Sky Tree (Fig.3) is a telecommunication tower of 634 m built in 2012. In consequence of earthquake safety study, engineers decided to set a large cylinder of reinforced concrete like Central column of old wooden pagoda's idea, as a vibration damping tool. (Fig.4)

The size of a central column set in an inner part between the lower part and the upper part is 375 m in height, 8 m in diameter and 60 cm in thickness. There is a stairway inside. "Tower's natural period is as long enough as 10 seconds. 40% of the response shear stress will be reduced compared with the case of no-cylinder" (Konishi 2011). The proportion of the main part height to the lower part width is 7.5 that is higher than the traditional pagodas, because of its peculiarity as a telecommunication tower. (Fig.5)

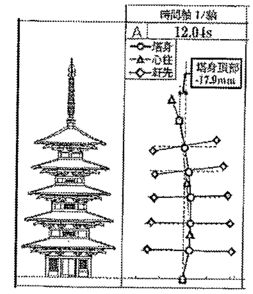

Figure 2. Distortion experiment by 1/5 model.

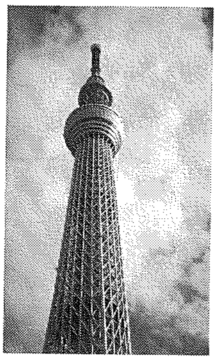

Figure 3. Tokyo Sky Tree.

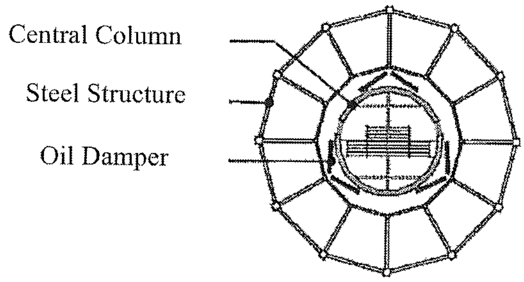

Figure 4. Central Column.

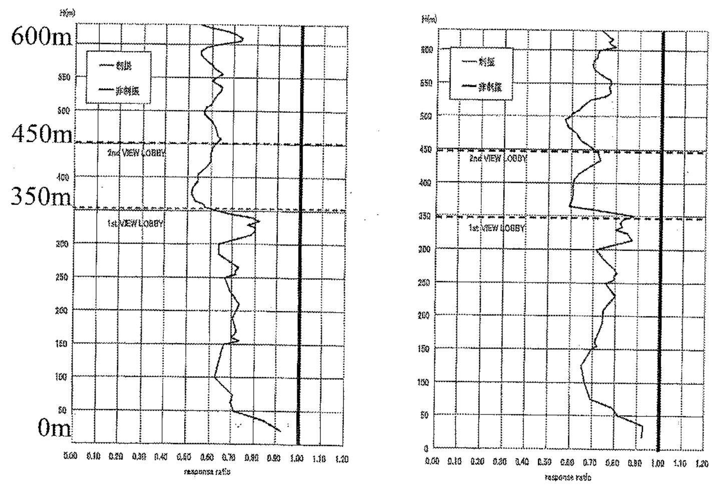

Figure 5. Effect of earthquake energy control by central column.

4.2 Marubiru Office Building, Tokyo

Marubiru (Fig.6) built in 2002 is located in front of the Tokyo Station. It is 37 storied and 178.5 m in height, with total floor area of 159,907.74 m^2. The philosophy of the structural design comes from Central column of a five storied pagoda. The earthquake proof shaft from the ground to the top floor was set in the center of floors. The shaft is connected with each floor by absorbing equipment. Experiment data show as follows (Fig. 8):

Case A: Without Central column: It would collapse.

Case B: With Central column, it resists. "The result of structural calculation with the maximum energy of the once-in-a-millennium earthquake, such as the Hanshin-Awaji Great Earthquake in 1995, shows that the earthquake damages disperse and the structure would survive. Maximum Layer distortion decreases by 60%"(Ogawa 2006). The proportion of height to width is 3.39 that is almost the same as the ratio of traditional pagodas.

Figure 6. Maru-biru.

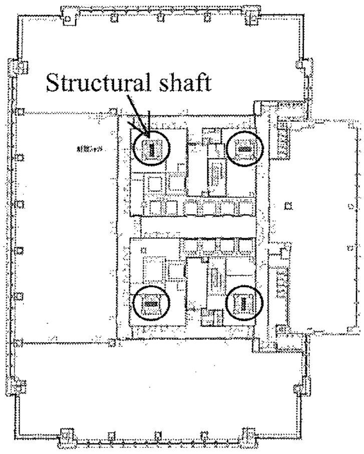

Figure 7. Floor Plan of Maru-biru.

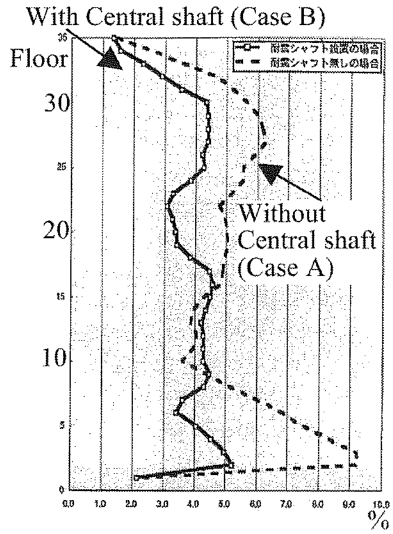

Figure 8. Max. Distortion of Floor.

5 CONCLUSION

(1) All 22 wooden five storied pagodas (built from 8th century till 19th century) have survived great earthquakes. The fact shows that they are earthquake proof buildings built by master carpenters empirically.

(2) Central column contributes to an earthquake proof structure. But details are not clear yet. Theoretical research has just started, and further interdisciplinary studies including structural engineering, traditional wooden architecture, earthquake science and etc. will be required to clarify the facts.

(3) The idea of Central column is applied to the recent structural design of remarkable modern architecture. In case of Tokyo Sky Tree, 40% of the response shear stress will be reduced. In case of Maru-biru, maximum layer distortion will decrease by 60% compared with the type of without Central column.

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