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EARTHQUAKE RESPONSE OF ANCIENT FIVE-STORY PAGODA STRUCTURE OF HORYU-JI TEMPLE IN JAPAN

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ABSTRACT

The architectural style of the five-story pagoda was brought into Japan from India via China in the 6th century. In Japan no pagodas have ever suffered serious damage from earthquakes. Even in the Great Hanshin-Awaji Earthquake, there were no reports of serious damage to wooden pagodas in Hyogo, Kyoto and Nara. This fact must be scientifically explained. Since the end of the Meiji era, many researches have studied the earthquake resistance of five-story pagodas. And several factors of earthquake resistance of them has been pointed out , such as friction damping and sliding effect of the wooden joints , base isolation effects , balancing toy effects of deep eaves , bolt fastening effect of the center column and so on. This paper attempts to evaluate and examine the earthquake behaviors of the ancient Japanese 5-story pagoda of Horyu-ji Temple through the response analyses.

1. INTRODUCTION

The architectural style of the five-story pagoda was introduced with Buddhism from India via China around the mid 6th century. During the years since then, about 1,300 years, many five-story pagodas encountered several huge scale earthquakes. There exist, however, no historical documents that report any toppling incidents of five-story pagodas except some damages in the ornamental element called kurin in Japanese in the top structure.

Even in the Great Hanshin-Awaji Earthquake Disaster of 1995 inflicted by an earthquake that registered a seismic intensity of M 7.2, there had been no reports on major damages to wooden pagodas close to the affected areas of Hyogo Prefecture or old pagodas in Kyoto and Nara.

These five-story pagodas are a mysterious existence for modern people in many respects. To understand one aspect of it, we conducted a simulation analysis of why the five-story pagoda of Horyuji Temple , shown in Figure. 1 , still standing in Ikaruga-no-sato in Nara has been so resistant to earthquakes.

Figure. 1: Photograph of the five story

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2. THE FORM AND STRUCTURE OF THE FIVE-STORY PAGODA OF HORYUJI TEMPLE

Five-story pagodas were built to enshrine Buddha's ashes (the skeletal remains of Buddha) and said to inherit the form of stupa, a style of tombs in ancient India. The five-story pagoda of Horyuji , regarded as the oldest existing wooden pagoda in Japan , was rebuilt around A.D. 711 after the original one was lost in a fire. Figure. 2 shows plans and sectional views of the pagoda. It boasts a total height of 32.55 m from its top to the top of its podium or 107.44 shaku, an older unit of length for Japanese.The plan of its structure is square with the length of its side, 5.45 m in the first through forth stories and 3.64 m in the fifth story. The first story is surrounded by a structure called mokoshi (an extra eave), an addition to the main structure that is covered with lean-to roofs. A center column supports its top structure, *sorin*.

The features of the five-story pagoda of Horyuji are described in the four points listed below. Further two more impressive features are the pliant impression suggestive of a flexible nature of its structure and deep eaves.

1. The ratio of the total height to the width of the main structure in the first story is 5.1.
2. The ratio of the width of the main structure in the top story and that of the first story is 0.51.
3. The ratios between the lengths of eaves and the widths of the main structure are 2.2 in the first story to 3.0 in the fifth story.
4. The ratio of sorin to the total height is 1:3.4.

The following six points can be listed as its structural features:

1. The main structural elements consist of wood.
2. There are many joints or connections such as the "kumimono" or complex joints connecting many wood members.
3. A framework in which each story is independent and no column ties them together.
4. The center column supports the ornamental structure on the top independently of the main structure.
5. The columns in the first story are not tied down to the foundation.
6. Its natural periods are around 1 second, and these are rather long considering the height of its structure.

In the original structure, the center column was buried in a deep hole in the ground, but it now stands on a base stone in the podium.

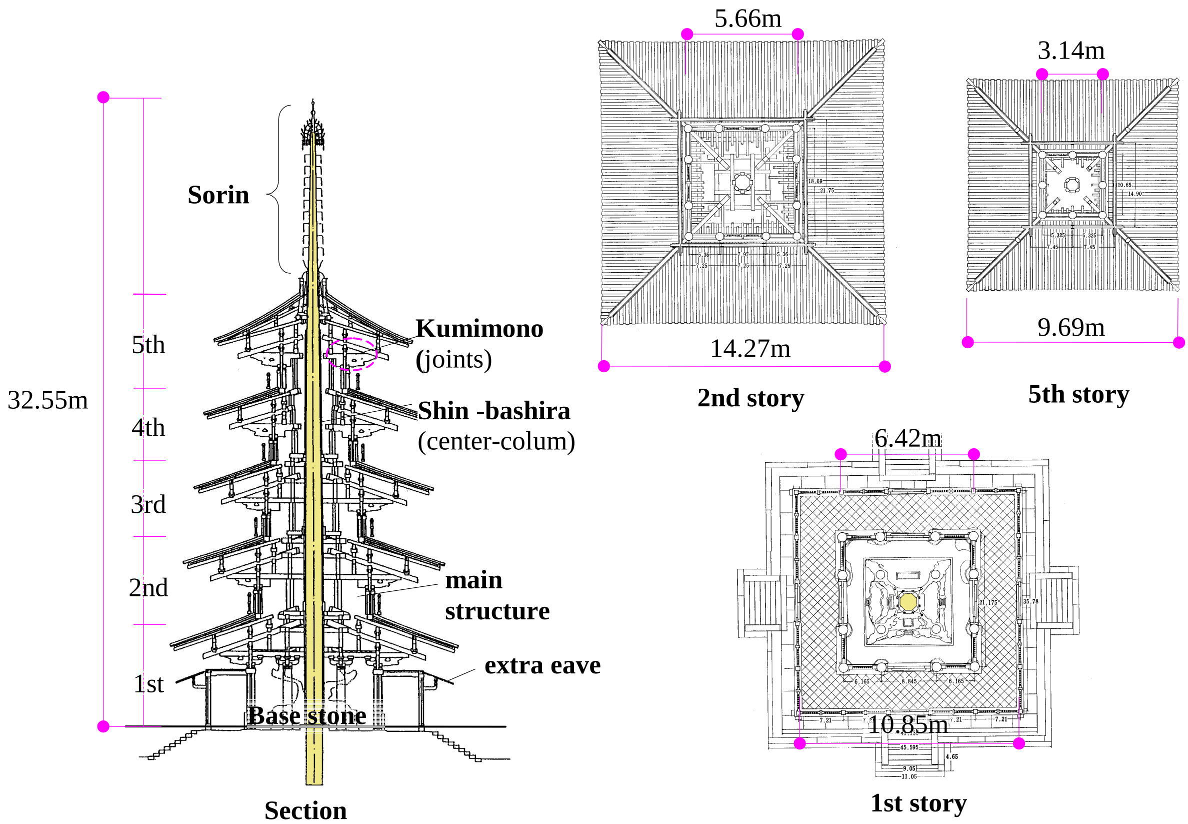


Figure. 2: Plan and sectional views of the pagoda

3. ANALITYCAL FOCUS OF THE STRUCTURAL ELEMENTS CONTRIBUTING TO THE EARTHQUAKE RESISTANCE

Many scientific researches have been conducted on the earthquake resistance of five-story pagodas since the end of the Meiji era (around A.D. 1900). Dr. Muto[3] thought the friction damping effect of the wooden joints was an important factor in making them earthquake resistant. After Dr. Ishida[2], the center column acts as a bolt fastening the whole structure and adding a restrainsing effect of shearing deformations among individual stories. According to the analyses conducted by Tanabashi[5], the factors increasing the resistance of the structure were the scale effect of the five-story structure , a characteristic of flexible structure and the wood joints' capacity for allowing plastic deformations through slipping or gaps in them. Dr. Ueda[6] considered that each structurally independent stories are mounted on top the other was able to allow each one to act like a balancing toy, cancelling the inertia force of each story out among them. And Dr. Omori proposed that the compound penduilam system , the center column and the main structure , gives TMD effect after researches of pagodas in Nikko-ji Temple and Senso-ji Temple.
Based on this background, seven factors , listed below and illustrated in Figure. 3, have been considered in the analysis.

1. Sliding between the base stones and columns contributing the earthquake resistance (base isolations)
2. Slipping and gaps in the wooden joints
3. Friction damping effect of wooden joints
4. Balancing toy effect (due to deep eaves)
5. Oscillation of the whole structure like a snake dance
6. Collision between the center column and the main structure , making a bolt effect
7. Center column TMD effect

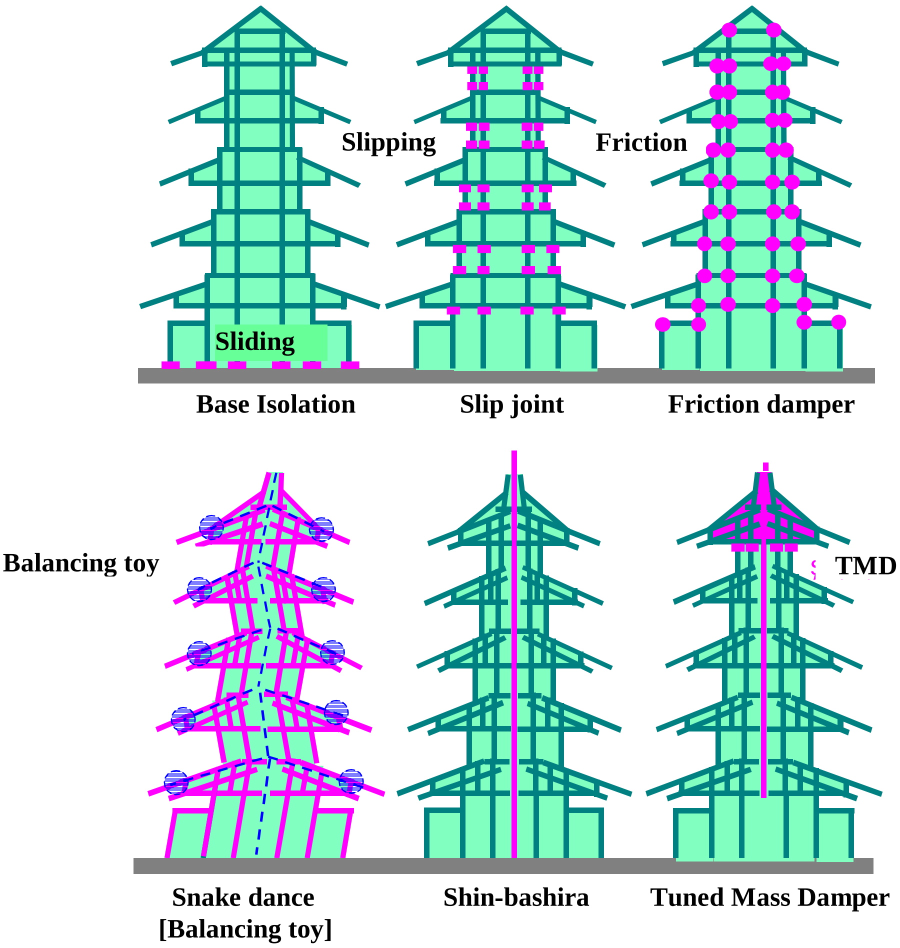


Figure . 3: Vibration control devices of the pagoda

4. ANALISYS MODEL

4.1 MODEL OF FIVE-STORY PAGODA

The structural model used in this analysis is the two dimensional frame shown in Figure. 4, and the column and beam members are assumed to be elastic. The mass of each story is concenntrated at several node points. The stiffness of the model frame are given as a result of referring to the Micro Tremor Measurement data by Dr. Uchida et al.[7], and the vibration period and modes of the first, second and third are shown in Table 1 and Figure. 5. The damping ratio of the column and beam members are assumed to be at 4% to critical based on the experimental observation by Dr. Uchida et al.[7] Also, the direction of analysis is set to be 45degree to the main structure , according to the report[8] by Dr. Yamabe and Dr. Kanai , the direction of the principal vibration of pagodas is considered 45degree to the main structure . The earthquake input motion is the N-S component of the 1995 Hyogo-ken Nanbu Earthquake, observed at Kobe station of Japan Meteorological Agency. The peak ground accelaration of the input excitation is 818cm/sec^2. The sway angle of each story at which the frame collapses is assumed to be 1/50 rad.

Table 1: Natural periods of the pagoda

	Natural period(sec.)	
	Micro-tremor[7]	Analysis
1st	1.11	1.13
2nd	0.42	0.49
3rd	0.24	0.33

4.2 VIBRATION CONTROLE DEVICES

4.2.1 *Slip joint and friction damper*

The whole amount of sliding and friction effects are attributed to the top parts of the columns of the analysis model. As shown in Figure. 6, they are assumed to act as a friction damper with the hysteresis characteristic of bi-linear frame with a 0.4 coefficient of friction within ±1.5 cm displacements, and they are represented by a non-linear spring sketched in the solid line in Figure. 6 and an equivalent damping factor.

4.2.2 *Base isolation*

Base isolation effect is also assumed by sliding and friction between bottom parts of colums at first story and the foundation is modeled using a non-linear spring shown in the solid line in Figure. 6.

4.2.3 *Shin bashira*

The gap between the center column and the main structure is set to be ±1 cm based on the restoration report of Horyu-ji.[1] Gap elements are placed between the center column and beams in the analysys model.

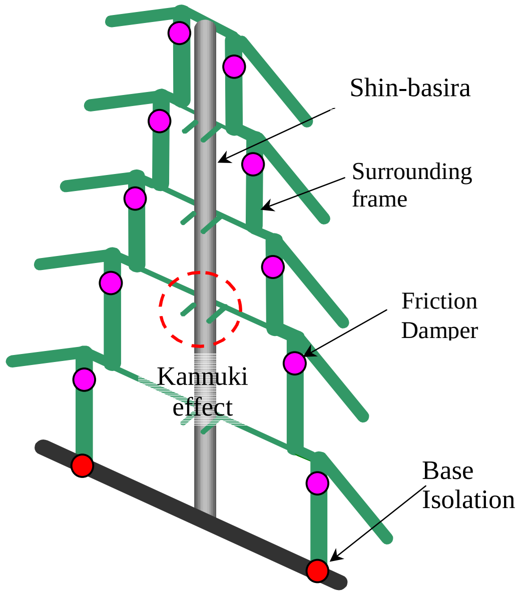


Figure . 4: Analysis model of the pagoda

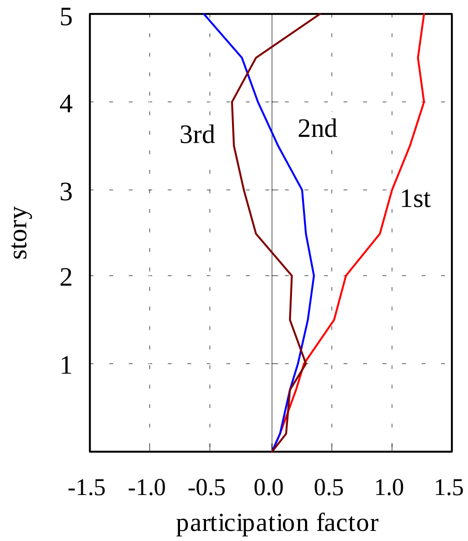


Figure . 5: Participation factor of the model

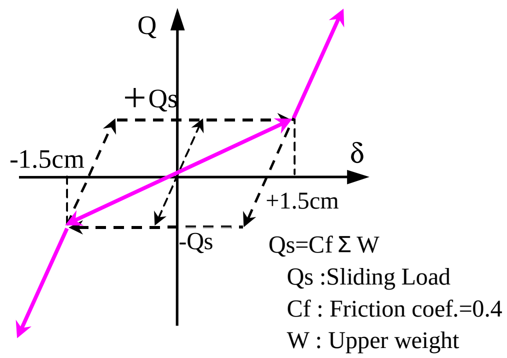


Figure . 6: Force-displacement characteristics of friction damper

4.2.4 *Balancing toy effect*
A balancing toy is equilibrated stably by gravity. When the balancing toy is excited and begins to rotate , the restoring momemt about the point O is applied as sketched in Figure. 7 (a). When a rotation angle θ is minute , the balancing toy effects are given by simple linear springs in the vertical direction as illustrated in Figure. 7 (b).

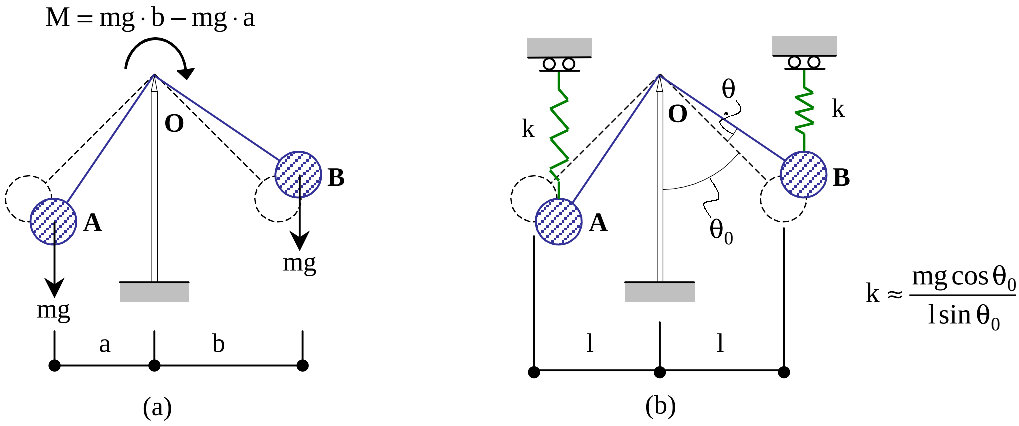
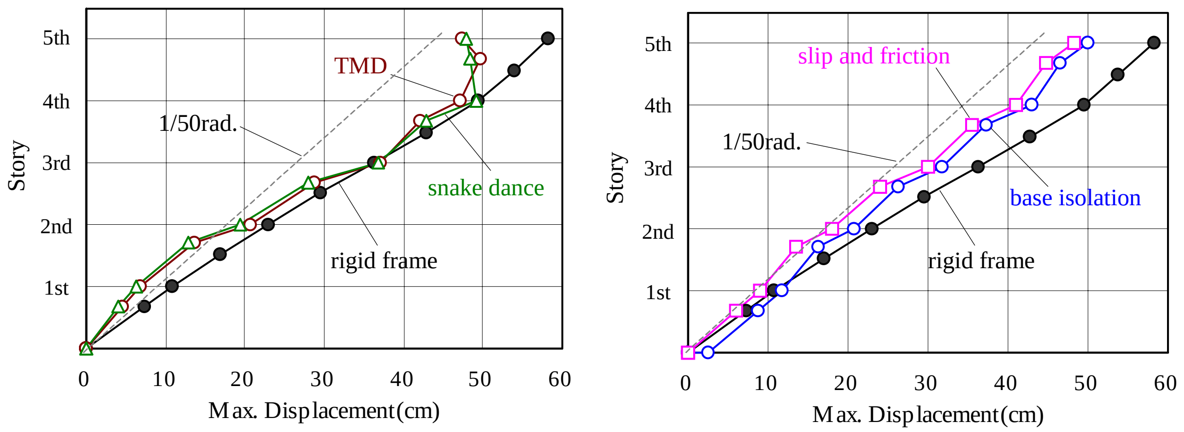


Figure . 7: Model of balancing toy effect

5. ANALISYS RESULTS

In Figure. 8 (a), (b), the envelope of maximum displacement responses against the earthquake of each model are shown in comparison with that of a conventional rigid frame structure model with its fundamental period of 1.1sec. Figure. 9 illustrates the envelope of maximum displacement against the earthquake of the composite model , including all vibration control effects , in comparison with that of the rigid frame model. And Time history of relative displacements of 3rd story and 5th story of the composite model against the earthquake at around the principal shock are shown in Figure. 10.
As can be seen in Figure. 8, the maximum displacement response of each model that includes only one vibration control effect is smaller than that of the rigid frame structure. The maximum response of each model , however , exceed the limit sway angle of 1/50 at which the frame may collapse.
Fig. 9 indicates that the maximum responses of the composite model is reduced to 56% of the maximum response of the rigid frame model, and the response sway angles are below 1/50, proving the integrated effect of many resistance factors that has been pointed out by researchers. Fig. 10 shows the time history of the relative displacement responses of 3rd and 5th stories of the composite model. The amplitude of the 3rd story is larger than that of 5th story at around the principal shock of the ground earthquake motion. This indicates that the intermediate stories behaves like as soft stories and act as isolators.



(a) TMD effect and Snake dance effect (b) Slip and friction effect and Base isolation effect

Figure . 8: Comparison of maximum displacements of each model

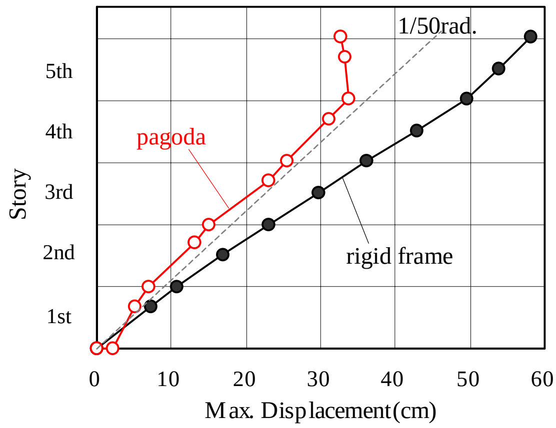


Figure . 9: Maximum displacement of the composite model

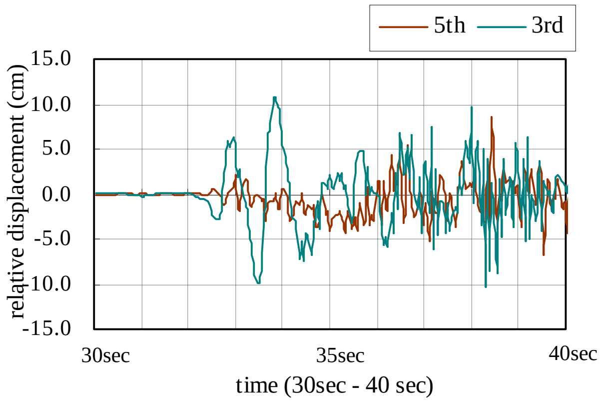


Figure . 10: Time history of relative displacements of the composite model

6. CONCLUDING REMARKS

The simulation study of the earthquake resistance of Horyuji's five-story pagoda proved that the pagoda has escaped the fate of collapsing in seismic excitation through an integrated effect of many resistance factors against earthquakes as has been pointed out by many researchers.
It should be emphasized that th mos effective factor for earthquake resistance of the pagoda may be the efforts of the faithful who have preserved the structure for such a long period of 1,300 years.

7. REFERENCES

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