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A study on aseismic properties of the five-storied pagodas

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ABSTRACT: The purpose of this study is to determine the effect of aseismic properties of the five-storied pagodas by using earthquake response analyses of an theoretical model. Such comprehensive model assumes shearing five-mass systems in both, i.e., the model of linear vibration with internal viscous damping and the model of nonlinear vibration with internal viscous damping and internal frictional damping based on the results of earthquake observations, microtremors observations as well as forced vibration tests carried out by one of the authors.

In the present investigation, we found that, when the vibrational periods of earthquake motions include the natural periods of the five-storied pagodas, the relative displacement of the five-storied pagodas occur as resonance phenomena. And we confirmed that the aseismic properties of the five storied-pagodas depend mainly on the internal frictional damping of the five-storied pagodas.

1 INTRODUCTION

The twenty-three five-storied pagodas (Gozyûnotos) in Japan were built from the 6th to the 19th century. The five-storied pagodas are constructed by wooden structure which structual form is not frame of rigid joint but the composite wooden-block structure (Masugumi), and there are built on comparatively relative hard ground. As to mention main particular feature, it may be not to report that the five-storied pagodas have been damaged by the past great earthquakes so far. As this problem aroused interest in earthquake resistant engineering and structural mechanics, studies on the effect of aseismic properties of the five-storied pagodas have been carried out by some Japanese investigators in the 20th century. The main factors of aseismic properties of the five-storied pagodas revealed in those paper were:

1) The five-storied pagodas did not have had resonanace phenomenon between the natural period of the five-storied pagoda and the vibrational period of the ground motions (Omori 1921, Suzuki 1969).
2) The five-storied pagodas could have a pretty large amount of vibrational damping (mainly internal frictional force of the composite wooden-block structure) (Muto 1929, Sezawa 1936~1938).
3) The vibrational energy of the five-storied pagoda was scattered in each floor by the central column (symbolize column (Shinbashira) becoming independent from the surrounding structual frames) of the five-storied pagoda (Ishida 1982).

But, we consider that the investigations on the effect of aseismic properties of the five-storied pagodas by using earthquake response analysis were still insufficient.

The purpose of the present study is to find this effect of aseismic properties of the five-storied pagodas by using earthquake response analyses of an theoretical model. This model assumes shearing five-mass system which is based on the results of earthquake observations, microtremors observations and forced vibration tests carried out by one of the authors (Yamabe 1988).

2 METHOD

The five-storied pagodas numbers by using earthquake response analyses comprise three. They stand for: Ikegamihonmon-ji Temple in Tokyo, Kofuku-ji Temple in Nara, and Hokan-ji Temple in Kyoto. We replace the model of the five-storied pagoda with shearing five-mass system. It is so difficult for us to replace the exact model from data based on the results of earthquake observations, microtremors observations and forced vibration tests, we replace the simple model by using following two assumption.

1)The models have shearing vibration.

2)The mass of each story (consentrated mass) is equal.

The total weights of the five-storied pagodas of Ikegamihonmon-ji and Hokan-ji estimated are based on relation between total hight and the result of estimation of total weight of Kofuku-ji. And the natural periods, the internal viscous damping factors and the vibration modes of three pagodas used, are the results of forced vibration tests of the five-storied pagodas. And we calculated the undecided stiffness by the shearing vibration formulated as the following (see Table 1):

$$\sum_{r=i}^{5} \omega^2 m_r u_r = K(u_i - u_{i-1}) \qquad (1)$$

where, $\omega = 2\pi/T$, T: natural period (sec), m: concentrated mass ($kg \cdot sec^2/m$), u: absolute displacement (m), and K: stiffness (kg/m).

The earthquake response analyses dealt with two method of both, the model of linear vibration with internal viscous damping and the model of nonlinear vibration with internal viscous damping and internal frictional damping. The numerical integration used β-method ($\beta = 1/4$) of Newmark. The total analysis time was 20 sec and by ticks off 0.02 sec.

The input earthquake motions used in the present study were EL CENTRO (NS direction ; 1940, maximun acceleration is 314 gal) in U.S.A., TAFT (EW direction ; 1952 maximun acceleration is 175 gal) in U.S.A. and SENDAI 501 (EW direction ; 1962 maximum acceleration is 47 gal) in Japan. The maximun acceleration of the input earthquake motions normalized 200 gal. Figure 1 show comparison of the normalized Fourier spectra between the result of microtremors observation of surface ground around the five-storied pagoda at Hokan-ji Temple and TAFT(EW) of the input earthquake motion, Figure 2 show comparison of the normalized Fourier spectra between the result of microtremors observation of surface ground around the five-storied pagoda at Ikegamihonmon-ji Temple and SENDAI 501(EW) of the input earthquake motion. From Figure 1 and Figure 2, we can see that two input

Table 1. Structual constants of the five-storied pagodas.

Name of Temple of the five-storied pagodas		Ikegami honmon-ji	Kohuku-ji	Hokan-ji
Natural periods (sec)		1.40	1.65	1.66
Internal viscous damping factors (%)		8.4	2.4	2.2
Total hights (m)		32.8	50.5	39.8
Total weights (Kg)		145×10^3	220×10^3	175×10^3
Stiffness ($\times10^5$ Kg/m)	5th	2.35	2.37	1.81
	4th	4.26	5.68	4.50
	3rd	6.76	7.42	6.23
	2nd	8.88	11.75	7.62
	1st	11.16	9.62	8.14

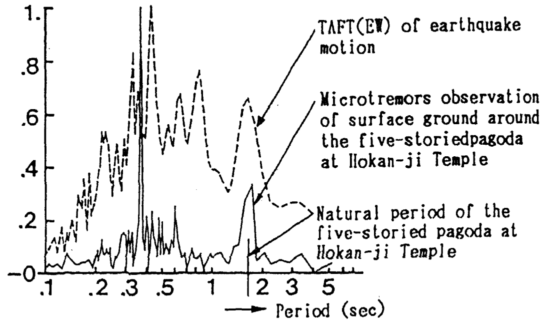

Figure 1. Comparison of the normalized Fourier spectra between the result of microtremors observation of surface ground around the five-storied pagoda at Hokan-ji Temple and TAFT(EW) of input earthquake motion.

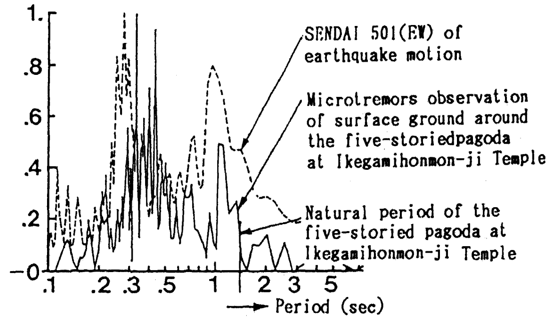

Figure 2. Comparison of the normalized Fourier spectra between the result of microtremors observation of surface ground around the five-storied pagoda at Ikegamihonmon-ji Temple and SENDAI 501(EW) of input earthquake motion.

earthquake motions agree fairy well with the ground charactaristics building of the five-storied pagodas.

3 RESULTS OF ANALYSES

3.1 Results of linear vibration analyses (considering internal viscous damping)

Figures 3~5 show the results of the distributions of the maximum relative story displacement of the three pagodas with only internal viscous damping by using the three input earthquake motions. In the three figures, we can see that the three pagodas vibrate at large relative story displacement on the fifth story of the five-storied pagoda. And the relative story displacements of each of the stories of Ikegamihonmon-ji is smaller than those of both Kofuku-ji and Hokan-ji. As to the reason of such result, we considered that the internal viscous damping factor including the five-storied pagodas were different in size (the internal viscous damping factor of Ikegamihonmon-ji was 8.4%, Kofuku-ji was 2.4% and Hokan-ji was 2.2%). Further, in Figures 3~5, we can see that the response values of the relative stories displacements of each of the stories, where the case of the maximum input acceleration of the input earthquake motions is 200gal, are very large amount. If the maximum relative stories displacements are converted into the stories deformation angles, the values of the stories deformation angles of the five-storied pagodas show about 1/200 at each of the stories, over 1/100 by the kind of input earthquake motions. From the results of the earthquake response analyses, the linear analyses in case of considering only the internal viscous damping, can not obtained, and hence the effect of aseismic properties of the five-storied pagodas can not be determined.

As the difference of the input earthquake motions of the each five-storied pagoda, in the case of Hokan-ji, the response values of the relative story displacement to input TAFT(EW) of input earthquake motion agreeing fairly well with the ground characteristics building of the five-storied pagoda, are larger than the response values of the relative story displacements to input the other input earthquake motions. As to the reason of this result, we consider the resonance phenomenon between the natural period (1.66sec) of having the five-storied

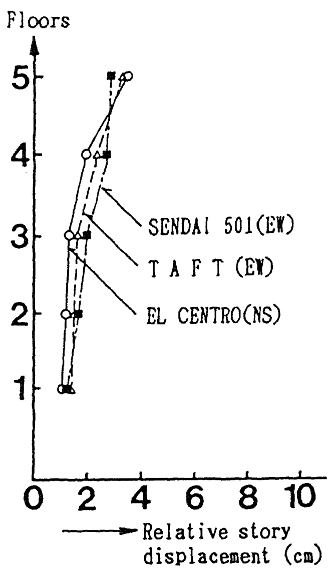

Figure 3. Distributions of the maximum relative story displacement of the five-storied pagoda by means of the difference in the input earthquake motions at Ikegamihonmon-ji Temple (considering the internal viscous damping).

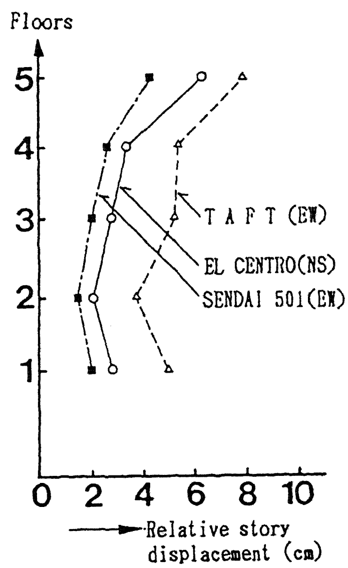

Figure 4. Distributions of the maximum relative story displacement of the five-storied pagoda by means of the difference in the input earthquake motions at Kofuku-ji Temple (considering the internal viscous damping).

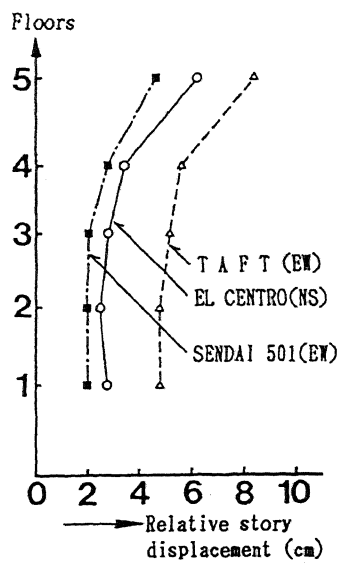

Figure 5. Distributions of the maximum relative story displacement of the five-storied pagoda by means of the input earthquake motions at Hokan-ji Temple (considering the internal viscous dammping).

pagoda at Hokan-ji and the vibrational period including TAFT(EW) of the earthquake motions (see Figure 1). Furthermore, we apply the same mean to Kofuku-ji. But, in the case of Ikegamihonmon-ji, the response values of the relative story displacements to input SENDAI 501(EW) of earthquake motions agreeing fairly well with the ground characteristics building of Ikegamihonmon-ji, does not possess the variation of the values of the relative story displacements to input other input earthquake motions further. As to the reason of this result, we consider that the period of earthquake motions comparatively similar to the natural period of Ikegamihonmon-ji do not include the period of SENDAI 501(EW) of the input earthquake motion further (see Figure 2).

From the results of the earthquake response analyses, even though the five-storied pagoda is built on comparatively relative hard ground, the seismic wave including both vibrational as well as natural period of the five-storied pagoda input, the relative stories displacement of the five-storied pagoda may increase if the resonance phenomenon is taken into consideration.

3.2 Results of nonlinear vibration analyses (considering internal viscous damping and internal frictional damping)

As analytical example of considering internal viscous damping and internal frictional damping, Figure 6 shows the response relative displacement wave on the fifth floor of the five-storied pagoda at Hokan-ji, for TAFT(EW) of the input earthquake motions; This case comparatively increase the response relative story

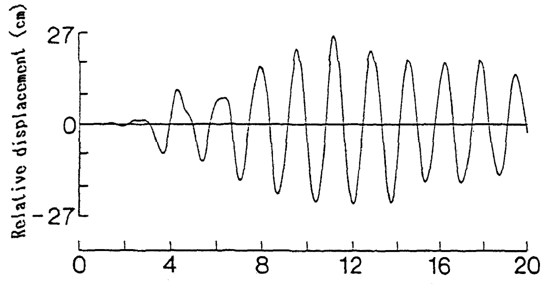

Figure 6. Response relative displacement wave on fifth floor of the five-storied pagoda at Hokan-ji Temple (considering the internal viscous damping and the internal frictional damping of constant), input earthquake motion is TAFT(EW).

displacement by linear vibration analyses. The internal frictional coefficent used the value of 0.044(cm/sec^2) based on results of forced vibration test of Hokan-ji. From Figure 6, the response relative displacement of the five-storied pagoda vibrates at the natural period of Hokan-ji, and the vibration of the five-storied pagoda contains large relative displacement and lasts over a long period of time. In these results, we can see that, even if internal frictional damping is considered, the response relative displacement of the five-storied pagoda shows large amount. In method of analysis of considering the internal viscous damping and internal frictional damping of constant, the results of the earthquake response analyses of this investigation contradict with past investigation on aseismic properties of the five-storied pagoda by the effect of internal frictional damping.

As one of the other ways on internal frictional damping, we carried out calculations based on results of the earthquake observations of the five-storied pagodas that the internal frictional damping of the five-storied pagodas increase with increasing the vibrational exciting forces. Figure 7 shows the distribution of relative

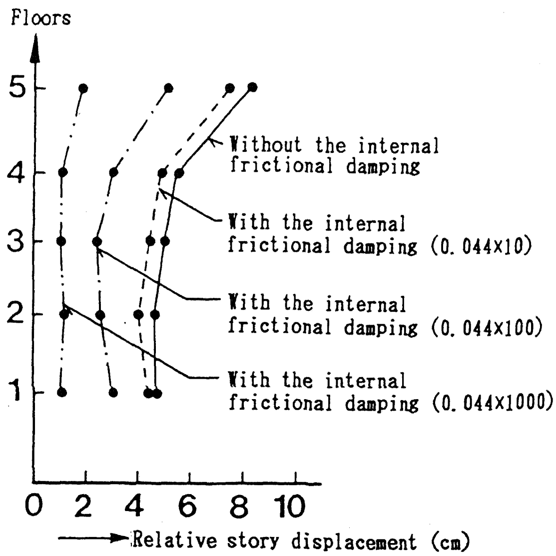

Figure 7. Distributions of the maximum relative story displacement of the five-storied pagoda by means of the difference in size of the internal frictional damping at Hokan-ji Temple (considering the internal viscous damping and the internal frictional damping proportion to the relative story displacement), input earthquake motion is TAFT(EW).

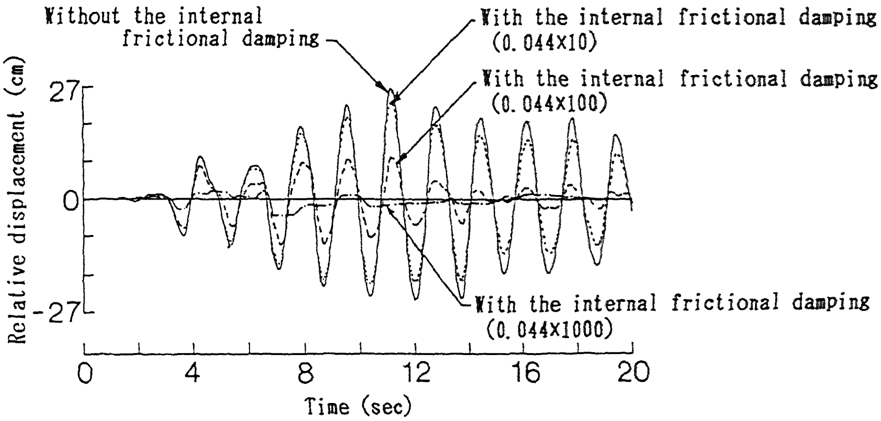

Figure 8. Response relative displacement waves on fifth floor of the five-storied pagoda by means of the difference in size of the internal frictional damping at Hokan-ji Temple (considering the internal viscous damping and the internal frictional damping proportion to the relative story displacement), input earthquake motion is TAFT(EW).

stories displacement of the each floor of the stories of the five-storied pagoda by means of the difference in size of the internal frictional damping, and Figure 8 shows the relative displacement wave on the fifth floor of the five-storied pagoda by means of the difference in size of the internal frictional damping. Furthermore, the internal frictional coefficents tentatively assumed in proportion to 10 times, 100 times and 1000 times of the relative stories displacements of each floor of the five storied pagoda. From Figure 7 and Figure 8, in the internal frictional damping tentativery assumed in proportion to the relative story displacements, the relative displacement of the five-storied pagoda is suppressed by internal frictional damping, we can clearly identify the aseismic properties of the five-storied pagoda by repression of vibration.

4 CONCLUSION

We conclude from the results of the earthquake response analyses of the five-storied pagodas described above the following:

1.The structure of the five-storied pagodas with linear vibration without considering the internal frictional damping, did not present the effect of aseismic properties.

2.In the case of earthquake motions including vibrational period as well as the natural period of the five-storied pagoda inputted in the five-storied pagoda, the response relative stories displacement of the five-storied pagoda may be increased by considering the resonance phenomenon.

3.As a matter of course, aseismic properties of the five-storied pagoda increase with increasing internal frictional damping. And, we have obtained that the internal frictional resistant of the five-storied pagodas increases with increasing vibrational exciting forces and this was based on the results of the earthquake observations of the five-storied pagodas in previous investigation by one of the authors. We have confirmed mathematically that the above results furnished further aseismic properties of the five-storied pagodas.

In conclusion, we wish to express our thanks to Dr.K.Kanai (former professor of the College of Industrial Technology, Nihon University) for many valuable suggestions in regard to this problem. We are also deeply indebted to Mr.M.Oba (Japan atomic power generation Co,.Ltd. at present) of our Laboratory for his considerable assistance with computer analyses.

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