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EARTHQUAKE RESPONSE MONITORING AND SEISMIC PERFORMANCEOF FIVE-STORIED TIMBER PAGODA

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SUMMARY

Traditional timber pagodas are believed to have high seismic performance, because although they have experienced many earthquakes during their lifetime, there is no document of a pagoda, which was destroyed by earthquake. The vibration characteristic of traditional timber pagodas in Japan is discussed based on the results of micro tremor measurement, free vibration test and earthquake monitoring. The experiment was subjected to a newly built timber pagoda, which was built by applying traditional structural system. The fundamental vibration characteristic of the pagoda is determined The natural frequency of vibration was approximately 1.5Hz and the damping factor 5%, the results of which are discussed in comparison with those of the preceding experimental researches. Although major earthquakes have not yet been recorded, the results of the earthquake response are compared with those of micro tremor measurement and free vibration test.

INTRODUCTION

Traditional timber pagodas in Japan are believed to have high seismic performance. This is because there is no document recording an evident collapse of a multi story timber pagoda by earthquake hazard, in spite of their height and low rigidity. Timber pagodas are monuments worshipping the bone of Buddha, and have been constructed in Japan since the 6th century, when Buddhism reached our country. Although the style was imported from China through Korea, only a few timber pagodas are left in both countries. Numerous pagodas have been constructed during the course of our history but the structural system has not changed fundamentally. The seismic performances of timber pagodas have been an interest for seismologists as well as structural engineers, and many analytical studies have been operated and hypotheses proposed. The seismic performance of traditional timber pagodas has not yet been clarified quantitatively, because of the lack of experimental data.
The object of the research is to clarify the seismic performance of traditional timber pagoda based on the results of micro tremor measurement, free vibration test and earthquake response monitoring.

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TRADITIONAL TIMBER PAGODAS

Outline

Historical Background

Timber pagodas are usually built in temples and shrines to enshrine the bone of Buddha. It is originated from *stupa* in sanscrit, which was built in Ancient India to worship the bone of Buddha after his death. The *stupa* was then introduced to China, where the structure is said to have combined with the native multi story building style and imported to Japan through Korea[i]. In Japan there are 22 existing five storied timber pagodas, which were built before 1850, all of which are designated as important cultural properties by the national government. The section and height of the five storied timber pagodas are shown in Fig 1 in the order of their construction year. The oldest is the pagoda of Horyu-ji, built in the 7th century. The natural frequency of the pagodas determined from preceding micro tremor measurements are shown together with the reference number.

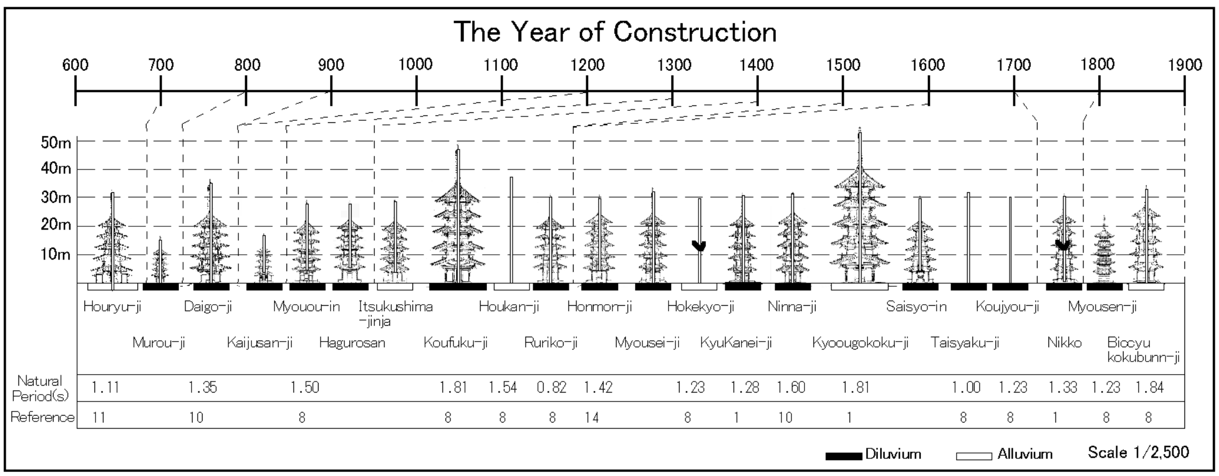


Fig.1 Sections of the Existing Five Storied Timber Pagodas in Japan, built before 1850

Structural System

The height of five storied timber pagodas range from 15 meter to over 50 meter. The structure has a square and symmetrical plan, usually three spans by three spans. The aspect ratio has a tendency to increase and the structure becomes slender for newer pagodas. The structural system of timber pagodas in Japan is composed of the center column and the surrounding multi story frame as shown in Fig.2. The center column is structurally independent of the surrounding frame structure, and is based on the foundation or on top of the beam of the first floor or suspended from the frame. On top of the center column, metal ornamentation called the *sourin* is installed. The columns of the surrounding frame are all based on top of the beam of the lower story, and have small aspect ratio.

Literature Review

Seismic performance of timber pagodas

The seismic performance of traditional timber pagodas has been an argument for many seismologists as well as structural engineers. The oldest experimental research was done by Omori[1], who conducted micro tremor measurements on six timber pagodas. Theoretical and analytical researches were operated by Sano and Taniguchi [2] and Sezawa and Kanai [3]. At the 2nd WCEE, which took place in Japan, Tanabashi gave a lecture on the earthquake resistance of traditional timber structures in Japan. He reviewed the preceding theories and pointed out that the assumed high earthquake resistance of traditional five storied pagodas are due to their structural damping and scale effect [4]. Umemura pointed out that the earthquake resistance of timber pagoda is due to small aspect ratio of the columns of the surrounding frame, the quantity of the horizontal members on each floor and the damping effect of the brackets [5]. Shiga and Shibata performed micro tremor measurement on a newly constructed five-storied timber pagoda [6], [7]. Experimental research was done by Kanai and Yamabe et.al [8] who determined the vibration characteristics of twelve timber five storied pagodas by micro tremor measurement. Kubota and Yamabe conducted structural analysis on a timber pagoda and pointed out that the timber pagodas do not have high seismic performance without considering the effect of friction [9]. Micro tremor measurements on three-storied as well as five-storied timber pagodas were conducted by Nishizawa[10] and Kawai, Maekawa and Uchida[11] to clarify the fundamental vibration characteristics. Structural design of a timber pagoda based on earthquake response analysis was carried out by Hanazato and Sakamoto[12]. Micro tremor measurement was also performed on aforesaid timber pagoda and the results compared with the analyses [13]. The correlation between historic earthquakes, which occurred near the pagoda, and the resulting damage was investigated by the authors[14]. The seismic performances of five-storied pagodas are revealed statistically. Seven documented damages at five five-storied pagodas were found, the amount of which are comparatively scarce to the earthquakes that took place.

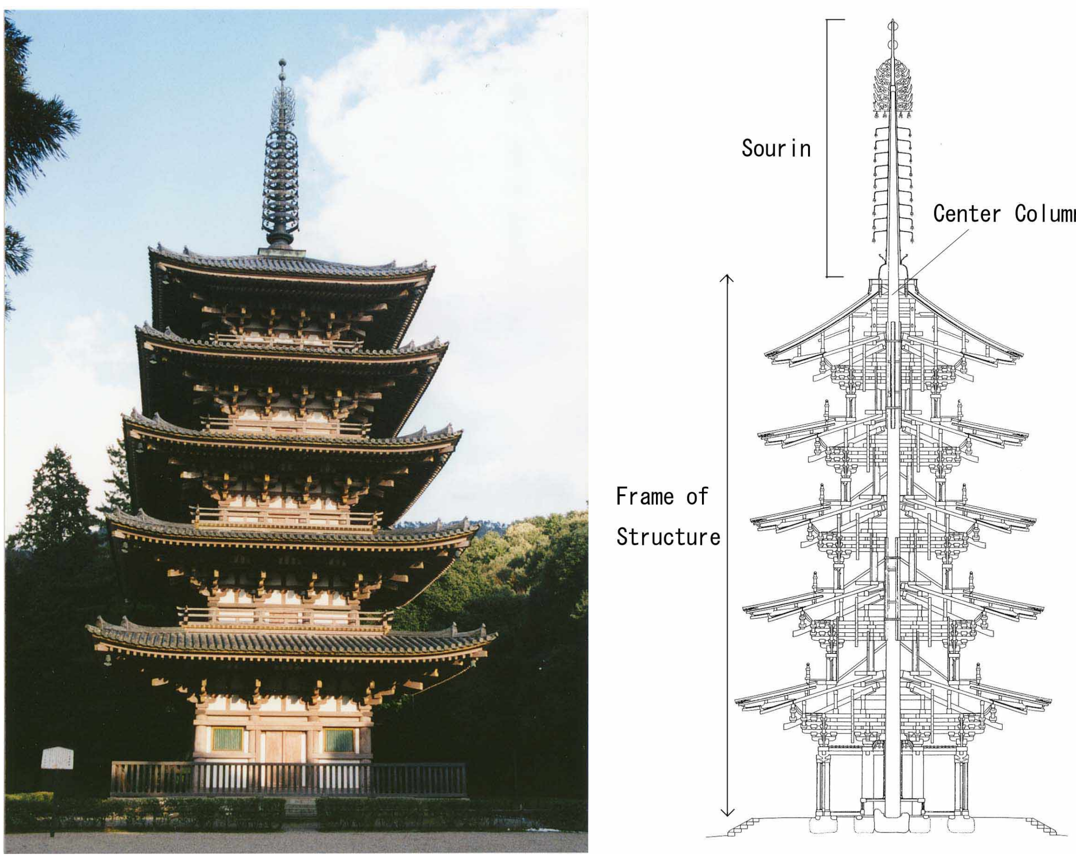


Fig.2 Example of the Section and Picture of Five Storied Pagoda (Daigo-ji Pagoda)

Natural Frequency

The natural frequencies of five storied timber pagodas obtained by preceding researches are shown in relation with the total height (Fig.3), and the height of the frame (Fig.4). The methods of experiment are all micro tremor measurements. The results show that the natural frequency of five storied timber pagodas range from 0.5Hz to 1.2Hz, the natural period of vibration 0.8s to 2s. The natural frequency of vibration is in inverse proportion to the square of the height of the structure. The tendency can be seen more prominently with the height of the frame rather than the total height of the structure.

The natural frequency of vibration is dependent on the mass of the structure and their rigidity. As the mass of timber buildings in Japan differs largely by the type of roofing, the average weight of each roofing type is shown in Table1. The equivalent natural frequency, which is the square root of the mass, is determined and normalized so that clay tile roofing would be 1.0, as shown in the right end line of the table. The measured natural frequency of timber pagodas as shown in Fig.3 and 4 is not effected by the type of roofing, as much as the calculated equivalent frequency. This suggests that for heavier type of roofing the rigidity of the structure is built to be higher.

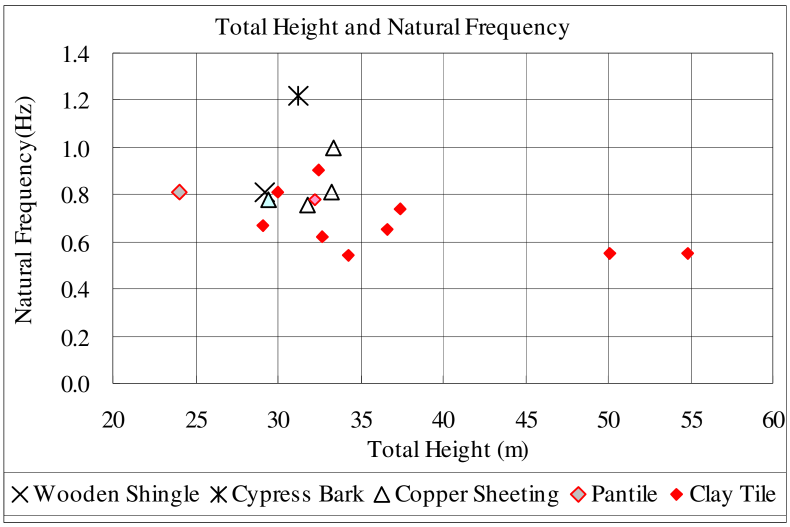


Figure3 Relation of Total Height and Natural Frequency of Five storied Pagodas

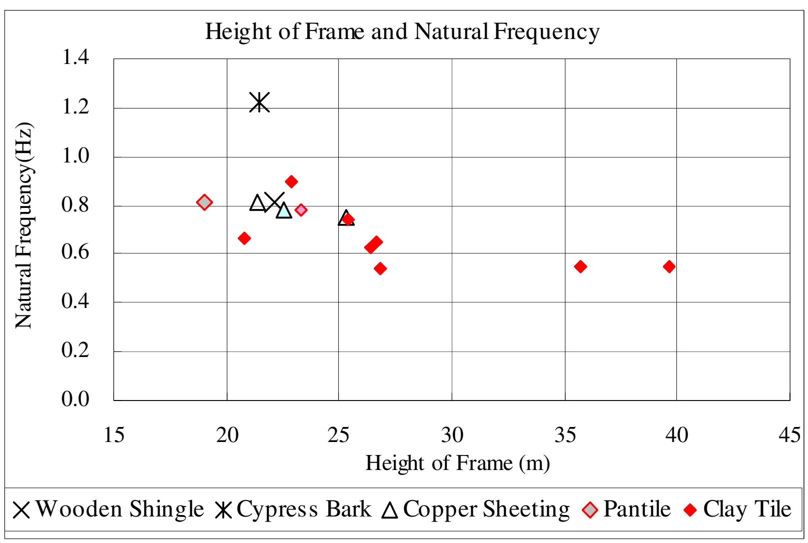


Figure4 Relation of the Height of Frame and Natural Frequency of Five storied Pagodas

Table 1

Type of Roofing	Weight per unit floor space (kgf/m^2)	Equivalent Normalized Frequency (Hz)
Clay Tile	250	1.00
Pantile	100	1.58
Cypress Bark	30	2.89
Wooden Shingle	10	5.00

From the results of preceding researches the earthquake resistance of traditional timber pagodas can be summarized as follows.

1. The earthquake resistance of five storied timber pagoda is generally high, because many of the timber pagodas have experienced severe earthquakes during their lifetime while their damage by earthquake is scarce.
2. The natural period of vibration of five-storied timber pagodas range from 0.8s to 2s.
3. The characteristic structure system of the timber pagodas, such as the brackets, center column and short thick surrounding columns are expected to be efficacious to earthquake resistance.

VIBRATION TESTS ON TSU-KANON PAGODA

Outline

Micro tremor measurement, free vibration test and earthquake response monitoring were conducted on a newly built five-storied timber pagoda in Japan.

Description of the Pagoda

The experiment was subjected to a newly built timber pagoda called *Keinichi san Kannon-ji Taihou-in Five storied Pagoda* (hereafter *Tsu Kanon Pagoda*) situated in *Tsu* city, *Mie Prefecture*, which is the central part of Japan. The Tsu Kanon Pagoda was constructed in May, 2001. The plan and section of the pagoda are shown in Fig.5 and Fig.6. The building was newly built by applying traditional timber structural system. The building is approximately 21m to the top of the *sourin*, the frame is 13m in height, 5m by 5m in plan. The structure is built on reinforced concrete foundation, the center column is set on a foundation stone installed on top of the RC foundation. All the timber used in the structure is cypress. The calculated weight of the structure was approximately 75 tons in total as shown in Table2.

Method of Experiment

Micro tremor measurement and Free Vibration Test

Micro tremor measurement and free vibration tests were conducted on September 2002 and December 2003. Data samples were measured for 60s by 100Hz, three times in each horizontal direction. The accelerograms were set on top of the beam on each story as shown in Fig.5 and Fig.6.

Free vibration test was operated by two persons pushing the surrounding column on the fourth story. The measurement was operated in the same method as the micro tremor measurement. The measurement was done three times for each direction.

Earthquake Response Monitoring

Strong motion accellerograms are installed in the pagoda and earthquake response monitoring is under operation. The devices were first set in July, 2002 on the foundation and the beam of third story, each with two channels in the horizontal direction. On September 2002 two accelerograms were added on the first and fourth stories, each one horizontal direction (EW). On August 2003 two more accellerograms were added on the first and fourth story, each in the NS horizontal direction. The location of the accelerogram is shown in the plan and section.

The sampling frequency was 100Hz, duration of measurement 60 seconds. High pass filter of 0.02Hz is used. Some examples of the acceleration records that have been obtained are shown in Table3.

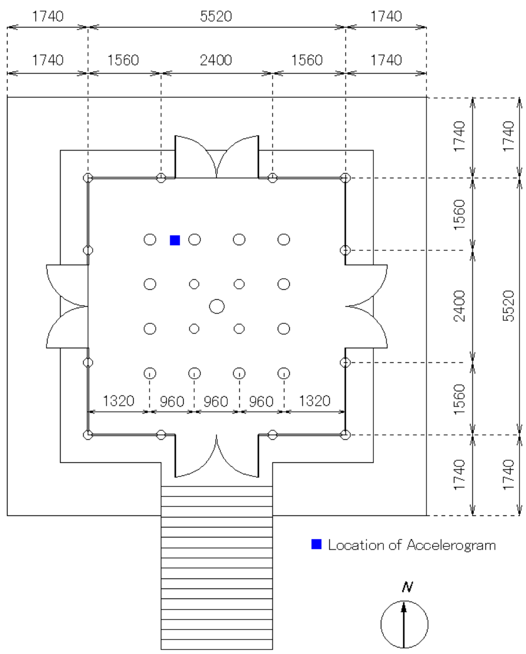


Fig.5 Plan of Tsu Kanon Pagoda

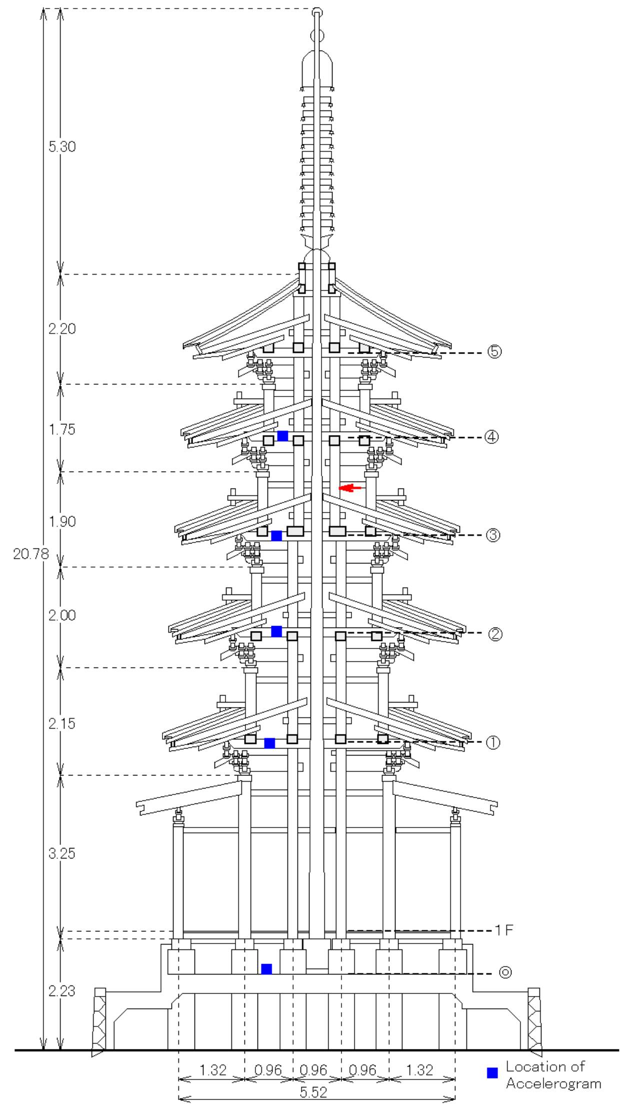


Fig.6 Section of Tsu Kanon Pagoda

Table2 Weight of Tsukanon Pagoda

	Weight (ton)
1st Story	30.16
2nd Story	11.40
3rd Story	10.71
4th Story	10.33
5th Story	11.38
Center Colum and Sourin	0.76
Total	74.74

Table3 Maximum Acceleration Measured by Earthquake Monitoring

		Maximum Acceleration (gal)							
Location of measurement		◎		①		③		④	
Date	Time	NS	EW	NS	EW	NS	EW	NS	EW
2002/8/11	7:56:34	2.91	4.29			3.88	8.62		
2002/8/11	23:00:44	1.17	1.15			1.33	2.39		
2002/8/18	9:01:50	0.86	0.66			2.09	1.75		
2002/10/20	0:26:57	1.18	1.22		−2.06	1.42	1.53		1.40
2002/11/27	15:22:45	6.07	3.75		−3.09	3.97	3.38		2.23
2002/12/9	3:21:26	5.24	4.41		5.53	−5.36	−4.58		3.90
2003/5/12	16:20:44	2.69	2.99		−0.17	−0.25	−0.17		−0.19
2003/5/18	3:24:13	1.87	−1.62		3.24	3.19	−4.12		2.57
2003/5/28	12:10:58	−0.66	−0.57		1.57	1.57	1.68		0.93
2003/7/6	8:31:24	1.94	−1.52		−4.55	3.58	4.29		−2.19
2003/7/9	2:14:30	−4.97	−7.55		10.98	−9.01	−8.42		−8.21
2003/8/12	13:52:33	2.81	4.51		0.13	−0.16	0.20		0.23
2003/11/11	7:55:11	2.91	3.65	−3.53	4.18	2.55	3.62	2.40	−2.72
2003/12/18	3:03:02	−6.56	3.61	−3.99	−5.15	6.55	5.23	6.40	−3.77
2003/12/23	14:35:11	−3.62	3.33	−4.72	−4.82	5.11	−5.31	3.35	−4.35

Results of Experiment

Response Displacement and Acceleration Record

Fig 7 and Fig.8 show the recorded response displacement of the pagoda on the first, third and fourth story by micro tremor measurement and free vibration test respectively. The acceleration measured on the foundation and the third story during the earthquake, which occurred on 2003, 5,28 are shown in Fig.9.

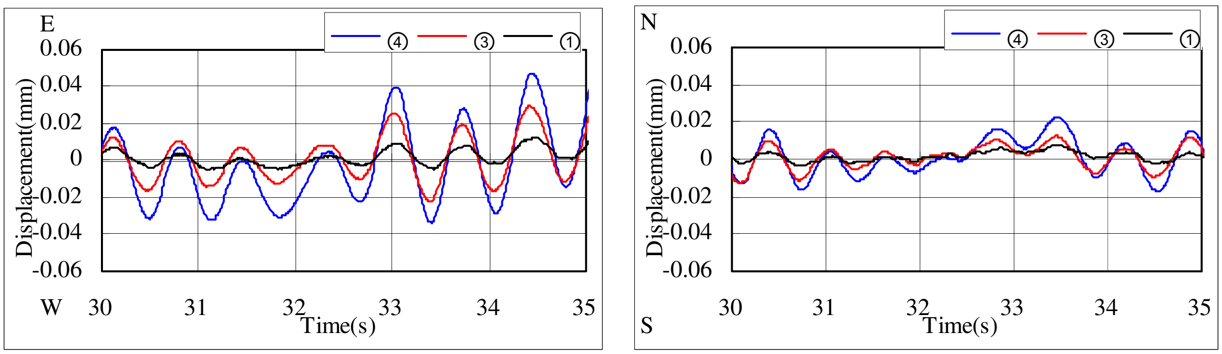


Fig.7 Response Displacement by Micro Tremor Measurement

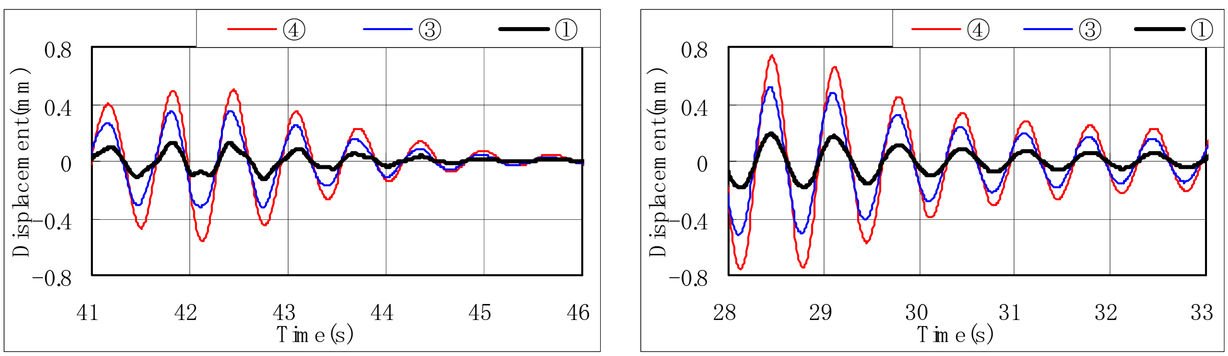


Fig.8 Response Displacement by Free Vibration Test

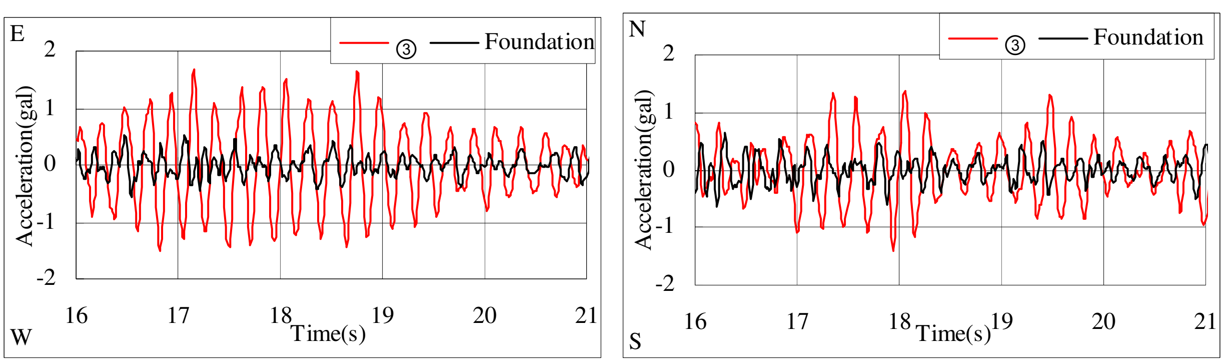


Fig.9 Response Acceleration by Earthquake of 2003.5.28

Natural Frequency of Vibration

The average natural frequency of vibration determined by the transfer function from foundation to the beam of the fourth floor is shown in Table 4. The natural frequencies of vibration were approximately 1.49Hz (first mode), 4.2Hz(second mode) and 7.2Hz(third mode). The values did not differ for NS and EW direction, resulting from the symmetrical plan. The transfer function from the foundation to the beam of each floor determined from the results of the micro tremor measurement and earthquake response is shown in Fig.11 and Fig.12 respectively.

The response amplitude of the second and third modes are substantially large compared to the first mode by earthquake response. This tendency was observed for earthquake response but was not observed for micro tremor measurement nor free vibration tests, the result of which will be discussed after.

Table4 Natural Frequency of Vibration

Natural Frequency	First Mode		Second Mode		Third Mode	
of Vibration (Hz)	NS	EW	NS	EW	NS	EW
Micr Tremor	1.440	1.432	4.150	4.053		
Free Vibration	1.465	1.553	4.209	4.004	6.983	7.056
Earthquake	1.556	1.511	4.264	4.235	7.256	7.279
Average	1.487	1.499	4.208	4.097	7.119	7.167

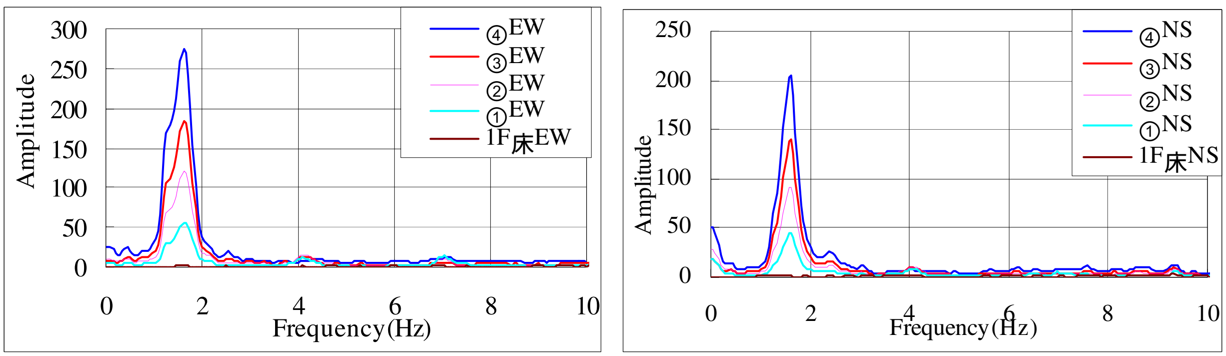


Fig.10 Transfer Function (Micro Tremor Measurement)

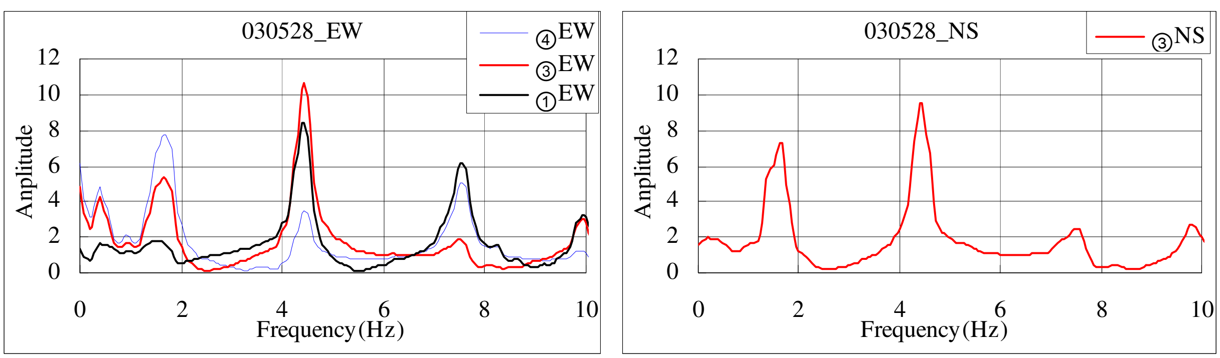


Fig.11 Transfer Function (Earthquake Response)

Vibration Mode

The vibration mode for the first and second modes determined from the amplitude of the transfer function from foundation to the beam of each story are shown in Fig.12. The vibration mode shows a typical bending mode.

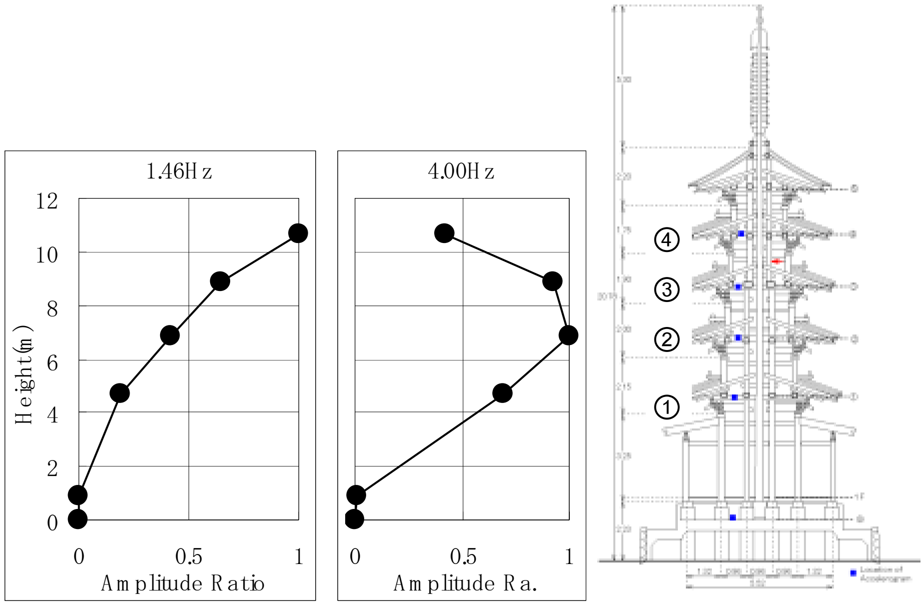
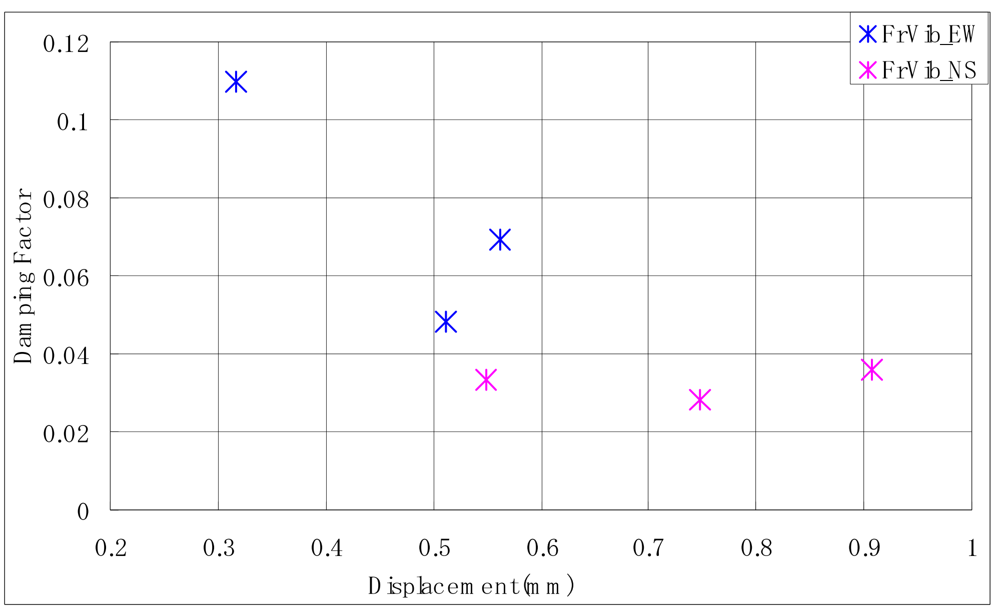


Fig.12 Vibration Mode

Damping Factor

The damping factor calculated from the logarithmic decrement of the response displacement of the free vibration wave profile is shown in relation with the maximum displacement of the fourth story in Fig.15. The values range from 0.02 to 0.1, approximately 5% in average. The result is consistent with those of the preceding experimental research, and is not very large compared to ordinary timber structures. No definite tendency can be observed with the relation of the maximum displacement.



FrVib: Free Vibration Test, EW: East West direction, NS: North South direction

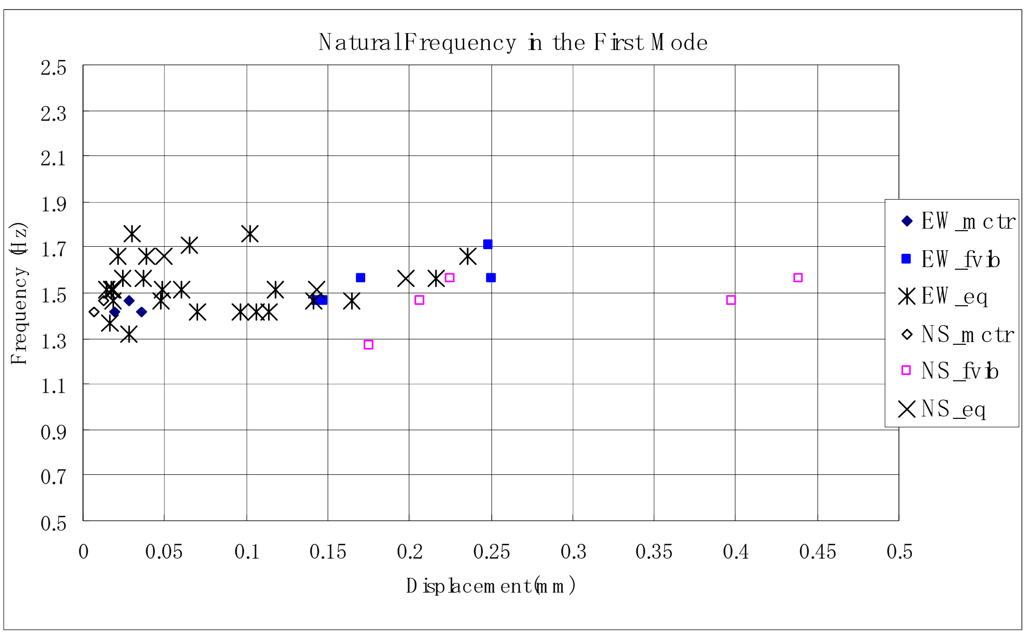
Fig.13 Damping Factor Determined from the Logarithmic Decrement of the Free Vibration Wave Profile

Discussion

The natural frequency of vibration in the first mode determined from the micro tremor, free vibration and earthquake monitoring is shown in relation with the measured maximum horizontal displacement of the beam of the fourth floor Fig.14. The natural frequency of vibration was determined from the transfer function from foundation to the beam of the fourth story as shown in prior Fig.10 and Fig.11. No major earthquakes have yet been recorded and the maximum displacement is equivalent to those of the micro tremor measurements. The natural frequency of vibration vary from 1.3 to 1.8 Hz, and is approximately 1.5 Hz in average. No definite relation with the maximum displacement is observed, which suggests that the non-linearity of the structure is not prominent in the displacement range of 0mm to 0.5mm.

The determined natural frequency of vibration in the first mode and the height of the frame of Tsu-kanon pagoda is compared with the results of the preceding research as shown in Fig.14. The frame of Tsu-Kanon pagoda, which was subjected to the experiment is approximately 13meters in height and the natural frequency 1.5 Hz. As the structure is small and newly built the consequent natural frequency is large. On the assumption that the natural frequency of vibration is in inverse proportion with the square of the height, the determined value is consistent with the result of the preceding researches.

The amplitude of the second and third modes were imperceptibly small from the micro tremor measurement, but the results of earthquake monitoring showed different tendency. This is discussed in relation with the wind load. Figure 14 shows the relation of the ratio of amplitude of the second mode to the first mode and the measured wind velocity at the time of the earthquake. The vertical axis shows the ratio of amplitude of the first mode A1 to the second mode A2. The horizontal axis shows the wind velocity measured at the time of the earthquake. The result shows that ratioA2/A1 is larger when the wind velocity is smaller. The amplitude of second mode is predominant when the wind velocity is small and the response of the structure is genuinely by earthquake.



mctr: micro tremor measurement, fvib: free vibration test
eq: earthquake response, EW: East West direction, NS: North South direction

Fig.12 Natural Frequency of Vibration in the First Mode

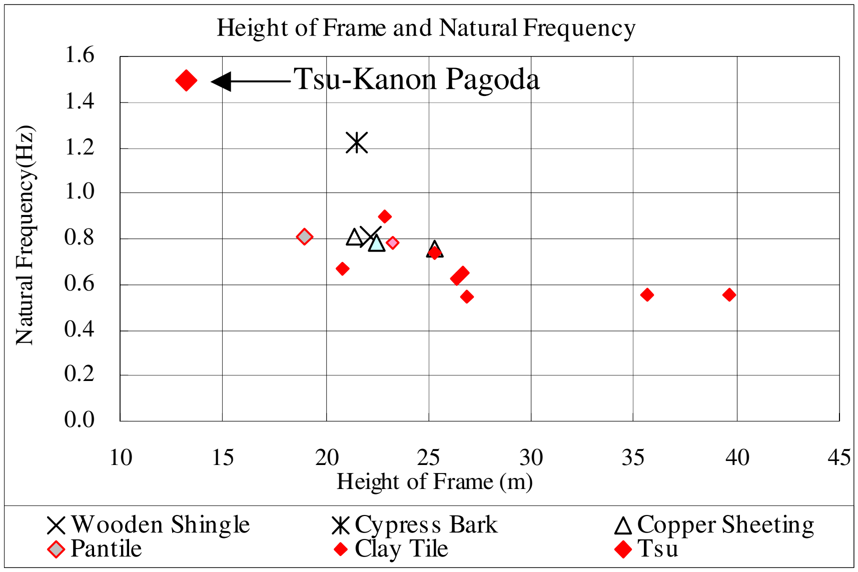
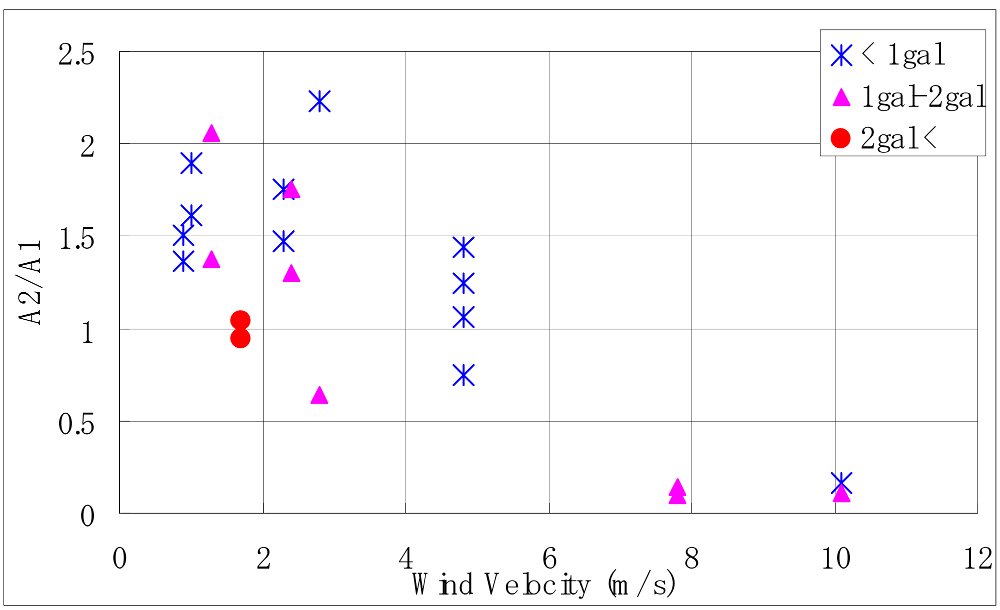


Fig.13 Relation of Height of the Frame and Natural Frequency of Vibration in the First Mode



A1: response amplitude of first mode, A2: response amplitude of the second mode
Fig.16 Relation of Wind Velocity and the Response Amplitude

CONCLUDING REMARKS

The seismic performance of traditional timber five-storied pagoda is discussed based on the results of micro tremor measurement, free vibration test and earthquake response monitoring. The experiment was subjected to a newly built five-storied timber pagoda is Japan. The fundamental vibration characteristics are determined. The natural frequency of vibration was approximately 1.5Hz and the damping factor 5%, the results of which is consistent with those of the preceding experimental researches. Major earthquakes have not yet been measured and the maximum acceleration recorded is 7.55 gal on the foundation. The non-linearity of the structure was not observed in the measured horizontal displacement range. From the results of the earthquake response, the second mode of vibration was observed to be prominent when the wind load can be ignored.

Acknowledgment

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[i] There are many theories concerning the origin of the timber pagoda.