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Seismic and Wind Performance of Five-Storied Pagoda of Timber Heritage Structure

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Abstract In Japan, there exist a total of 22 five-storied timber pagodas constructed before the middle of 19 centuries. All of those pagodas are registered as the important cultural heritages by Japanese Government, while some of them are listed in World Cultural Heritages such as Horyu-ji Temple's Pagoda that was built in the end of 7th century. As those timber pagodas in seismic areas have survived against earthquakes during their long histories, their earthquake resistant capacity has been studied for a century. However, the actual dynamic behaviors of timber pagodas subjected to large earthquakes should be recorded to understand the seismic performance. Furthermore, an interesting structural issue has recently risen of wind resistant capacity of traditional five-storied timber pagodas, as such tall timber structures may be severely affected by strong wind. In order to record the actual dynamic behaviors during not only earthquakes but also typhoons, we have been conducting earthquake and wind monitoring at Hokekyou-ji Temple in Ichikawa City, next to Tokyo, which has survived for 4 centuries against not only large earthquakes but also severe typhoons. Hence, while the earthquake monitoring has been done by the conventional method utilizing accelerometers, the dynamic displacement of the structural response to wind has been directly measured by a new technique employing an image process system using LED makers and CCD camera, because the wind response includes much longer period component in general, therefore, it must be difficult to measure accurately the wind response by accelerometers. The scope of the present paper are 1) to review the past studies to understand the excellent earthquake resistance of five-storied timber pagodas, as well as, to introduce our research project of seismic and wind monitoring that has been successfully conducted since 2007, 2) to interpret those monitoring records which would be useful for understanding seismic and wind performance of the heritage timber pagodas that have survived for many centuries with describing the simulation analysis of seismic response, and 3) to show the long term monitoring records of the horizontal displacement of the heritage structure.

Keywords: Heritage structure, monitoring, microtremor, five-storied timber pagoda, earthquake, wind, typhoon, long term deformation

Introduction

Japan is a seismic country, where most of historical buildings had been constructed of timber. Also, typhoons often hit the Japanese islands with strong wind and heavy rainfalls. One of the typical timber

structures that had been developed in Japan after having been introduced first from the Chinese mainland is a multi-storied pagoda. In the ancient time before 8th century, a number of seven- and nine-storied timber pagodas were constructed, however, Japanese history's literatures described that all of those pagodas were destroyed by fires or by strong wind. On the other hand, five-storied timber pagodas in Japan have survived against strong earthquake motions for many centuries. As one of the representative historical buildings of timber, the five-storied pagoda in Hoyu-ji Temple, World Heritage, in Nara (See Photo.1) constructed in the end of 7th century is the oldest timber structure in the world. This World Heritage pagoda has been subjected to a number of historical earthquakes for 13 centuries. Although slight damage to the pagoda in Horyu-ji Temple were caused during some of historical earthquakes, for example, the decorative pole was broken at its base on the roof of 5th story by the great earthquake of 1361, the structure itself has been survived. Fig. 1 shows a picture of earthquake damage to the five-storied pagoda in Asakusa Kannon Temple in Tokyo, drawn in 1854 Ansei-Edo Great Earthquake. Unfortunately, this pagoda was destroyed by the fire during the World War II. Now, we have a total of 22 historical five-storied timber pagodas existing in Japan, having been constructed before the middle of 19 centuries. All of these historical pagodas were registered and protected as the important cultural properties by Japanese Government. For seismic studies of timber pagodas, it should be considered that there is neither record nor document describing that five-storied timber pagodas collapsed during large earthquakes. This excellent experience of earthquake-proof indicates that traditional timber pagodas in Japan have inherent great potentialities against earthquakes.

Photo 1: The oldest timber building of existing five-storied pagoda in Horyu-ji Temple, World Heritage

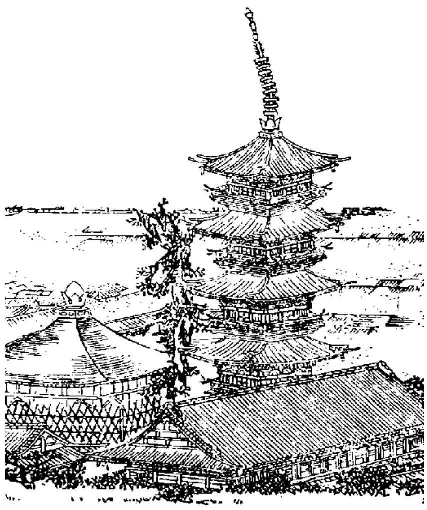

Figure1: Damage of decorative pole of five-storied pagoda in Tokyo by Great Ansei-Edo Earthquake of 1854 (after F. Ohmori, 1921)

The Japanese prominent researches who developed earthquake engineering in the last century studied this subject to understand the excellent earthquake-proof structure. In the present paper, those past studies of the earthquake-proof are first reviewed for introduction. After the Great Kobe Earthquake of 1995, research on traditional timber structures became very active in Japan, because thousands of old timber houses were destroyed by that devastating earthquake. Among a number of such studies conducted after this disaster, the shaking table tests of 1/5 scale model structures of the historical timber pagoda were conducted by us (Chiba,K. et.al. 2007) to study their dynamic behaviors (See Photo.2). Furthermore, earthquake monitoring was conducted to record actual behaviors during earthquakes at a newly constructed five-storied timber pagoda (Fujita,K. et al.2004). Studies of the traditional timber buildings after the Great Kobe Earthquake enabled us to conduct structural designing of five-storied pagodas. Structural designing of a new five-storied pagoda of traditional timber construction was successfully conducted and the microtremore measurement was performed

after completion to compare the dynamic characteristics of the construction with the structural designing analysis (Hanazato,T.,2004,See Fig.2). As introduced above, those recent studies dealt with the scaled model structures or a newly constructed timber pagoda, implying the necessity for the study at the actual historical pagoda. Therefore, in order to exactly understand the inherent earthquake resistant capacity, it had been needed to deal with the historical timber five-storied pagoda that survived for many centuries against large earthquakes.

Photo 2: 1/5 Scaled model structure of timber five-storied pagoda in Horyu-ji Temple for shaking table test

Photo 3: Collapse of the five-storied pagoda in Shitennou-ji Temple,Osaka by Muroto Typhoon of 1934 (after the Asahi Shinbun)

On the other hand, in general, such high-rise and light structures of timber are affected by wind. In fact, the five-storied timber pagoda in Shitenno-ji Temple, Osaka, totally collapsed by the Muroto Typhoon in 1934 (See Photo.3) , one of the strongest typhoon that has hit Japan so far. This disaster indicated that a five-storied timber pagoda was not safe against strong wind. In consideration of this experience, timber pagodas were strengthened against wind loads, when new timber pagodas were structurally designed in the last decade. However, it should be emphasized that the other historical five-storied and the three-storied timber pagodas existing in Kaisai district (Osaka, Kyoto, Nara) where they were severely affected by that strongest typhoon survived. This experience also suggested, on the contrary, that timber five-storied pagodas might withstand considerable strong wind. However, only a few studies were conducted on wind resistance of Japanese multi-storied timber pagodas. For examples, the wind tunnel tests using small models were performed to study wind resistance (Ohkuma,T. et al. 2004) or to structurally design a new timber five-storied pagoda. Some analytical studies were also conducted us to study wind performance of traditional five-storied timber pagodas (Katagiri,J. et al. 2005). In order to discuss the potentiality of wind resistance, it should be essential to record the actual behaviors of a five-storied timber pagoda that survived for many centuries against severe typhoon. In the present research, not only the earthquake monitoring but also the wind monitoring have been successfully conducted at the historical five-storied timber pagoda that has withstood large earthquakes and strong typhoons for four centuries.

Interpretation of Excellent Seismic Performance by Past Studies

Earthquake-proof properties of Japanese timber five-storied pagoda have been scientifically studied for a century by famous researchers to interpret why they have not collapsed during strong earthquakes. Omori,F. (1921) tried to explain it by scale effect meaning that overturing resistance of a structure would become larger as its size was larger. He also studied vibration control effect of a suspended central column. Sezawa,K. and Kanai,K. (1936) studied theoretically their anti-seismic properties by employing elastic wave propagation model, as shown in Fig.3. They pointed out that damping condition due to not only friction at bracket complexes and the other joints but also dissipation energy into ground would be effective in reduction of response to ground motions. Yamabe,K. and Kanai,K.(1988) ,Kubota,H. and Yamabe,K.(1992) conducted a series of microtremor measurements of the historical timber five-storied pagodas since 1970's. In the present research, by

following their studies, microtremor measurements at a total of seven historical five-storied timber pagodas were performed to complete the database of the fundamental dynamic characteristics. Ohba,S. And Kinoshita,K.(2002) also conducted the microtremor measurements at a number of historical three- and five-storied timber pagoda. Timber multi-storied pagodas in Japan can be categorized into flexible structure from an earthquake engineering point of view. Muto,K.(1963) introduced “ flexible design concept” to interpret the good seismic performance of the Japanese timber five-storied pagodas by comparing it with “rigid design concept” of nuclear power buildings. “Flexible design concept” means the structural situation where seismic forces are reduced under the condition that response spectra at longer period become lower. In general, fundamental natural period of a timber five-storied pagoda is rather longer than the predominant period of earthquake ground motions, which has considerable effect in reducing seismic loads, being similar to seismic performance of modern high-rise buildings. Furthermore, seismic behaviours of Japanese traditional timber structures are affected by non-linearity of rigidity. In particular, the ancient timber constructions were characterized by piling up method of structural members, which might cause high non-linearity with large damping, as introduced by Sezawa,K. and Kanai,K.(1936). As structural rigidity of such structures strongly depends on strain-level, the equivalent natural period becomes longer at higher response level during large earthquakes, which means that the resonance causing serious damage would not be likely to occur. This effect of non-linearity also must be significant for such “flexible structural designing”. Another dynamic phenomenon for seismic safety is “collision effect” proposed by Ishida,S. et al.(1994,1994), who studied it by shaking table test of small model structures (See Fig.4). He expected that collision, which caused energy transmitting and dissipation between layers through central column, might occur between a frame structure and a central column when a pagoda was subjected to extremely strong ground motions, and at the same time, suffered large structural deformation. When collision occurs, a central column also might have effect in restricting excessive deformation of the story drift of the frame.

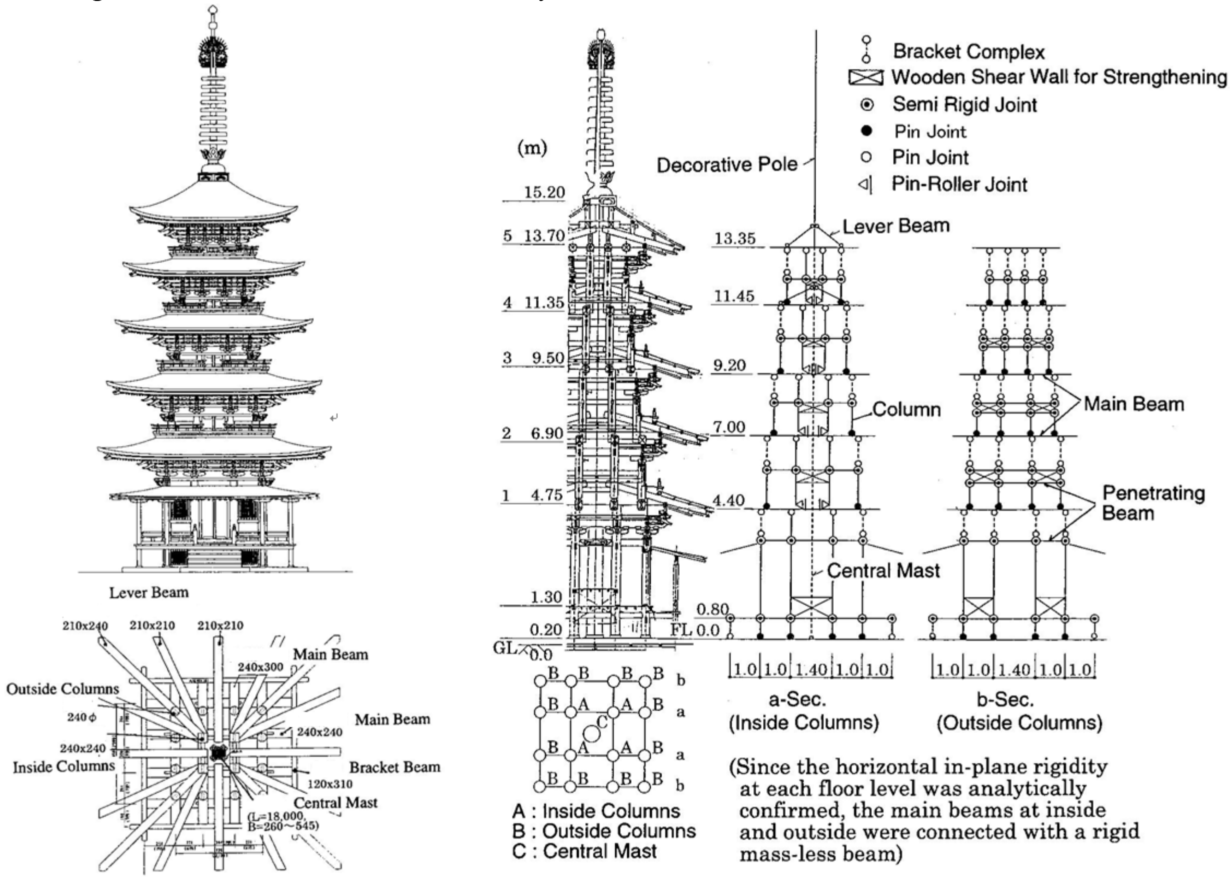

Figure 2: 2-demensional frame model provided for non-linear structural designing analysis of a new pagoda (Hanazato et al.2004)

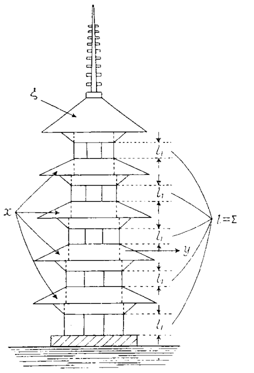

Figure3: Analysis model using 1-demensional wave propagation theory of five-storied pagoda (after Kanai and Sezawa, 1936)

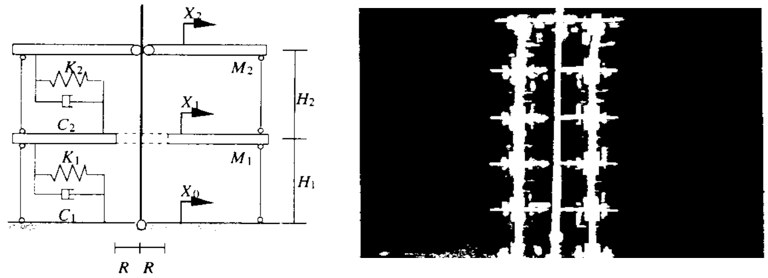

Figure 4: Analysis model and model structure for shaking table test to study "collision effect" (after Ishida 1994)

Incidentally, remember that about 70% of the buildings destroyed by the Great Kobe Earthquake in 1995 were caused by structural unbalance that means irregularities of rigidity along height or eccentricity in horizontal in-plane. In this sense, a traditional -storied timber pagoda in Japan can be categorized into well-balanced structures without any irregularities from an earthquake engineering point of view. Such experience indicated that the structural balance should be the most essential factor of the inherent potentialities against earthquakes. Furthermore, bracket complexes which can act as dampers are regularly arranged in each story. Well-balanced arrangements of a number of bracket complexes must improve the seismic performance as a vibration control system.

As introduced, a number of mechanical reasons why Japanese five-storied timber pagodas are earthquake-proof structures have been proposed for a century. However, although each factor is effective in improvement of seismic performance, we should consider a total structural system of a five-storied timber pagoda, i.e., it excellent anti-seismic resistance is achieved from a total of each factor. In other words, there is no week point in the structure against earthquakes from an earthquake engineering point of view. Even if one of those functions happens to be lost, the other inherent anti-seismic factors would cover it, therefore, the structure would still safe against large earthquakes.

Structural Characteristics of Five-Storied Pagoda in Japan

The architectural history argued that the ancient timber pagodas in Japan were originated from the Indian stone/soil stupa of the symbolic relics of Buddha. The technique of the construction of multi-storied pagodas had been developed in the mainland of China (Ishida,S. 1994) The ancient original structural concept of multi-storied timber pagodas in Japan was brought around 7 century together with Buddhism Culture from the Asian countries, i.e.; China and Korea. The most famous construction existing is the five-storied pagoda in Horyui-ji Temple, constructed in the end of 7^{th} century. As found in Horyu-ji Temple, the ancient original constructions were done by piling up of timber elements of columns, beams and bracket complexes by insertion of dowels at the interfaces, shown in Fig.5. It is interesting to note that such condition of the joints is similar to dry masonry construction in ancient Europe as Parthenon Athens, Greece (See Fig.5,Hanazato et. al 1999).

The structural characteristics of the ancient timber construction in Japan can be summarized as; 1) Comparatively large damping effect at the joints is caused with high non-linearity, 2) Conspicuous improvement in shearing resistance is produced by dowels connecting the elements, and 3) Generation of restitutive force produced by rocking movement of a column. One of the most remarkable structural elements of a Japanese pagoda is a central column that stands independently from the surrounding frame structure. Ishida,S (1994) discussed "collision effect" of the central column on the seismic safety, introduced in the previous section(See Fig.4). It should be also considered that those ancient timber structures might have not survived without the history of restoration. Since the ancient period, the structural concept of the timber construction had been

successfully improved by Japanese master carpenters. One of the most advantageous techniques of restoration of timber structures is disassembling and reassembling of the members. The five-storied pagoda in Horyu-ij Temple has a history of structural restoration. During its long history, the pagoda was disassembled (partially or totally) and reassembled several times with replacing the deteriorated elements by new materials. However, owing both to the excellent properties of the original materials, in particular, Japanese Hinoki tree, and to the good conditions at the site, approximately 80% of the timbers materials are surviving from the original construction. Another important factor was the form of the building. The ancient construction of timber pagodas had deep overhanging eaves covered with thick and heavy roof tiles, shown in Photo 1, as buildings in Japan was affected by heavy rainfalls. However, such heavy roofs sometimes caused serious structural problem, large creep deformation of eaves due to the gravity. In order to solve this problem, the light materials of bark or bronze plate were usually used after the medieval period as the roofing materials for new construction of pagodas. This alteration of roofing materials also might contribute to improvement of seismic performance, but might not contributed to wind performance. During the history of the improvement of timber structures in Japan, a penetrating beam might be the most significant element among the various techniques. After penetrating beams were introduced in Japan for strengthening technique of timber frame structures in 13th century, the timber structures had been constructed or restored by employing penetrating beams which must have contributed the improvement of seismic safety. This alteration means that the piling up construction technique in the ancient period changed to the frame structure during the medieval period.

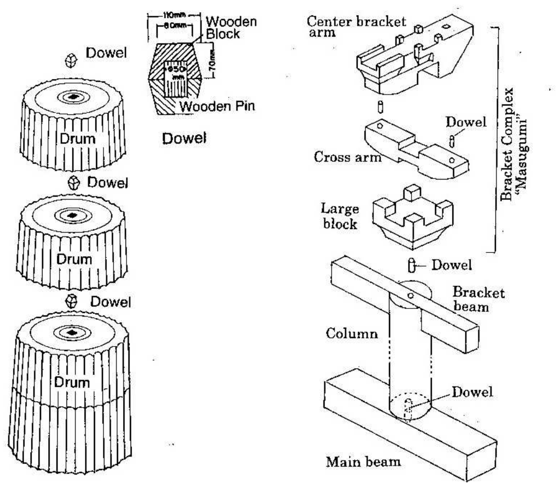

Figure 5: Comparison of ancient constructions of Greek masonry and Japanese timber temples – Piling up of structural members

Fundamental Dynamic Characteristics assessed by Microtremor Measurements

The authors conducted a series of microtremore measurements at 7 sites of the historical five-storied timber pagodas registered as the important cultural properties by Japanese Government, and finally completed the data base of the fundamental dynamic characteristics of the historical five-storied heritage timber pagodas constructed before the middle of 19 centuries. In the present study, the earthquake and wind monitoring have been conducted in the five-storied timber pagoda in Hokekyou-ji Temple(See Photo 4), one of those heritage pagodas. Before starting the monitoring at the site, the microtremore measurements were performed to investigate the fundamental dynamic characteristics. The final measurement for the data base was carried out at the five-storied pagoda in the Kaijyusen-ji Temple, Kyoto(See Photo5).This pagoda was constructed in 1214 and has survived against large earthquakes and strong typhoons. One of the most essential dynamic characteristics is the fundamental natural period. To summarize the data base of a total of 22 pagodas, Table 1 shows the relationship between the fundamental periods and the height of the pagodas, as the period is

considered to be correlated with the height of the structure. Fig.6 describes the relationship between the height of the structure and the fundamental natural period. The empirical equation to express the relationship between height and natural period can be statistically derived as;

$$T=0.39H \text{ (s)} \quad (1)$$

where H denotes height of a pagoda

The damping factor obtained by the free vibration tests that were conducted so far during the microtremore measurements ranged from 1.6% to 5.3% with the mean value of 2.5 %, shown in Table 1.

Photo 4: Five-storied pagoda in Hokekyou-ji Temple

Photo 5: Five-storied pagoda in Kaijyusen-ji Temple

Table 1 Summary of microtremor measurement results

Temple	Construction year	Total height (m)	Frame height	Roofing	Natural period (s)	Damping factor (%)	Note
Horyu-ji (WH)	680	32.6	22.9	Tile	1.11	4.0	Our study
Murou-ji	800	16.1	11.5	Bark	0.78	5.3	Ooba
Daigo-ji (WH)	952	38.2	25.4	Tile	1.39	1.8	Kanata
Kaijyusenji	1214	17.7	12.7	Tile	0.88	2.7	Our study
Myououin	1348	29.1	21.5	Tile	1.36	2.3	Kanai
Hagurosan	1377	29.3	22.2	Shingle	1.20	1.6	Kanai
Itsukushima (WH)	1407	28.4	21.2	Bark	1.15	3.4	Our study
Kofuku-ji (WH)	1426	50.1	35.7	Tile	1.95	3.5	Kanai
Houkanji	1440	38.9	26.7	Tile	1.63	2.2	Kanai
Ruriko-ji	1442	31.2	22.7	Bark	1.00	4.9	Kanai
Ikegami Honmon-ji	1607	29.3	23.4	Tile+Copper	1.14	1.6	Kanai
Myojyo-ji	1618	33.9	24.1	Shingle	1.32	1.8	Our study
Hokekyo-ji	1622	30.8	22.4	Copper	1.23	1.6	Our study
Kannei-ji	1639	32.3	24.1	Tile+Copper	1.38	1.4	Fujita
To-ji (WH)	1643	54.8	39.6	Tile	1.85	2.5	Ooba
Ninna-ji (WH)	1644	35.9	26.4	Tile	1.68		Kanai
Saisyoin	1666	31.3	21.9	Copper	1.20	2.1	Our study
Daiseki-ji	1749	33.4	28.8	Copper	1.02	1.5	Kanai
Kosyou-ji	1808	30.0	24.0	Tile	1.24	1.5	Kanai
Toushyo-gu (WH)	1818	34.5	26.3	Copper	1.28	1.7	Our study
Myousen-ji	1825	24.1	18.2	Tile	1.28	1.4	Kanai
Bityukokubun-ji	1825	34.2	27.4	Tile	1.45	3.0	Kanai

Seismic Monitoring

It is recommended in ICOMOS Guideline that direct observation of the structure is an essential phase of the study for investigation of the structure. It is also recommended that dynamic monitoring is used

to record accelerations in seismic areas. In general, non-destructive or minor-destructive tests should be used for detailed structural assessment of heritage structures. As a non-destructive test for seismic assessment of heritage structures, seismic monitoring is one of the most practical and effective methods. In the present study, the earthquake monitoring has been performed since 2007 at the five-storied timber pagoda in Hokekyo-ji Temple(See Photo.4). This pagoda was constructed in 1622 in the beginning of Edo era, and structurally restored in 1743, 1864 and 1912. During its long history, it has been subjected to large earthquakes and strong typhoons for 400 years, but has survived. The height of the pagoda including the decorative pole at the top was 30.8m, which was approximately the mean height of the historical pagodas, shown in Table 1. The roofing materials of this pagoda are copper plates, indicating that this timber pagoda is lighter than the pagoda utilizing tiles with a mud layer for roofing. The total weight of the timber pagoda was estimated to be 1420kN (1st story =400kN,2nd story=260kN,3rd story=250kN,4th story=240kN,5th story=270kN). The central column was suspended by iron chains. Such hanging technique of the central column was developed in 19th century for the countermeasure against the long term vertical displacement of the surrounding frame due to the creep phenomenon (to avoid damage due to relative displacement between the central column and the surrounding frame structure). For the case of Hokekyo-ji Temple, the hanging technique of the central column was introduced when it was restored in 19th century. The microtremore measurements showed, in both X and Ydirection, that the fundamental natural period and the damping factor were 1.19(s) and 1.8% ,respectively. Fig. 7 shows the accelerometer arrangement installed for the earthquake monitoring. Shown in Fig.7, the accelerometers were installed to record the dynamic motions on not only the surrounding frame structure but also on the central column. A total of 18 components have been monitored without trigger system (continuous monitoring) with sampling interval of 0.01s (100Hz).

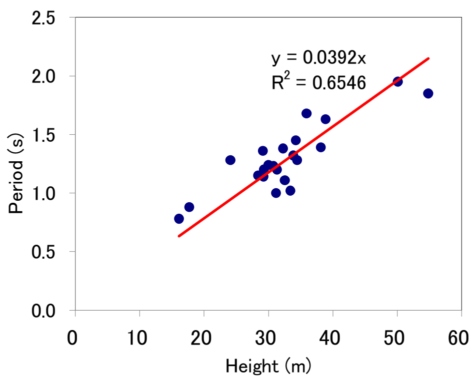

Figure 6: Relationship between height of pagoda and fundamental natural period

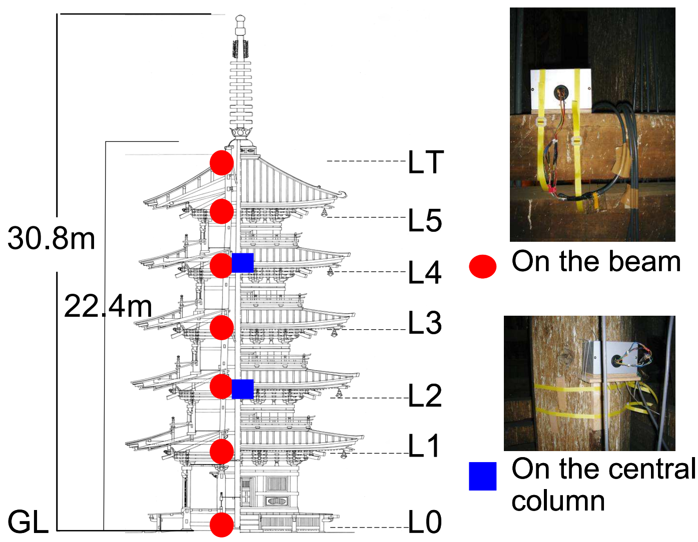

Figure 7: Earthquake monitoring at the five-storied pagoda in Hokekyo-ji Temple

The earthquakes recorded since April 2007 is outlined in Table 2. Among the recorded earthquakes listed in Table 2, the Ibaragiken-oki Earthquake of May 8, 2008 is appropriate for describing in the present paper. Fig.8 shows the deformation of the frame structure at the time when the peak response displacement and acceleration were observed at the top during this moderate earthquake. Fig.9 also presents the vibration mode shape of 1st , 2nd and 3rd modes with the natural periods of 1.51s, 0.54s, and 0.22s, respectively. It should be noticed that the fundamental period recorded during the earthquake (1.51s) was rather longer than that obtained by the microtremore (1.19s). This significant shift of the natural period was caused by the strain-dependent (so-called non-linearity) effect being specific to such traditional timber structure. In order to understand this effect of the displacement

level on the natural period, the relationship between the relative horizontal displacement at the top from the base and fundamental natural period is described in Fig.10, where the various earthquake data listed in Table 2 are included. It should be recognized in Fig. 10 that the natural period becomes longer as the displacement level is larger.

Table 2 List of earthquakes recorded

Earthquake	Occurrence date	Magnitude Epicentral distance	Direction	Ground motion	Peak response acceleration at top	Max. response acc. ratio	Max. relative disp	Max. story drift
				cm/s^2	cm/s^2		mm	
Tokaido-oki	Aug. 9, 2009	6.9	X	20.1	61.0	3.0	4.0	1/5300
		320km	Y	19.4	45.6	2.4	5.3	1/4000
Tochigiken-nannbu	Dec. 18,2009	5.1	X	8.1	39.4	4.9	1.4	1/15000
		80km	Y	7.6	30.4	4.0	1.7	1/12600
Niigataken Chuetsu-	Jul.16, 2007	6.8	X	8.2	28.6	3.5	4.6	1/4600
		230km	Y	7.3	29.1	4.0	6.8	1/3100
Chibaken toho-oki	Aug.16, 2008	5.3	X	10.7	20.4	1.9	3.9	1/5500
		60km	Y	10.3	19.1	1.9	3.3	1/6300
Ibaragiken -oki	May. 8, 2008	7.0	X	24.5	49.2	2.0	9.5	1/2200
		180km	Y	18.8	48.6	2.6	10.8	1/2000
Iwate-Miyagi Nairiku	Jun. 14,2008	7.2	X	8.9	27.2	3.1	7.1	1/3000
		420km	Y	6.6	32.2	4.9	8.0	1/2600

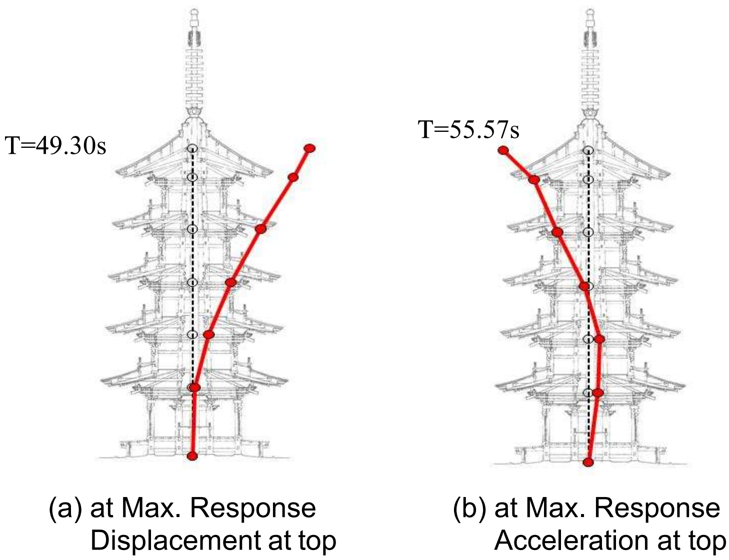

Figure 8: Displacement curves of structure at peak response relative displacement and peak response acceleration

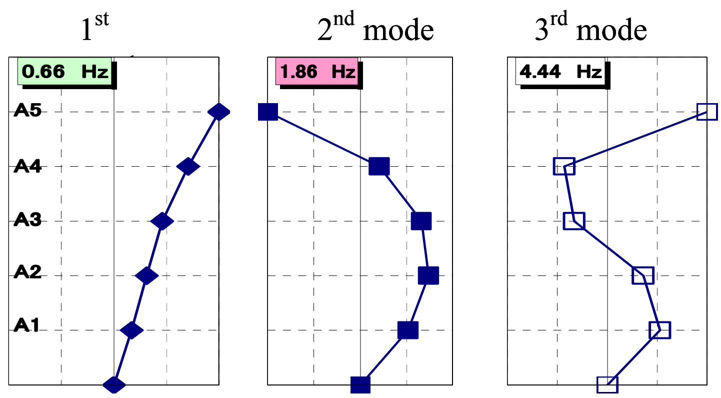

Figure 9: Natural frequency and modes in horizontal X-direction observed during the Ibaragiken-oki Earthquake

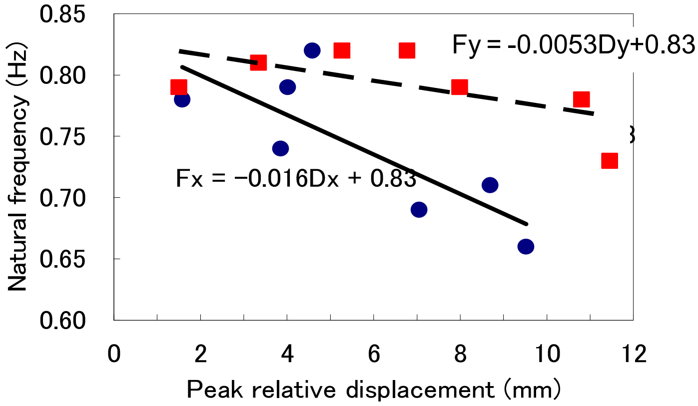

Figure 10: Relationship between peak relative displacement and natural frequency

In the present study, the earthquake response analysis was conducted to simulate the dynamic behaviours during the Ibaragiken-oki Earthquake of May 8, 2008 by employing a simplified lumped masses stick model shown in Fig. 11. Described in Fig.11, the main frame structure was modelled by lumped messes connected by shear elements. On the other hand, the central column was modelled by beam elements. The stiffness of the shear spring of the main frame structure was determined by identification to agree the analysis with the observation. Rayleigh damping (6% for 1st mode, 4% for 2nd mode) was employed to perform the response analysis. Fig.12 compares the simulated acceleration wave form with that observed at the top of the structure. A good correlation can be found in this figure, indicating that even such simplified model is useful for the earthquake response analysis of a timber pagoda. To examine the effect of the central column on the response of the main frame structure, the earthquake response analyses of the model not only with the central column but also without it were performed. Fig.13 compares the observed maximum response acceleration distribution along the height of the frame structure with the analysed ones of the two models. It can be recognized in Fig.13 that the analyses results of the model with the central column are in good agreement with the observation at the upper stories of the pagoda. This figure also indicates that the central column can be effective in reducing the response of the pagoda.

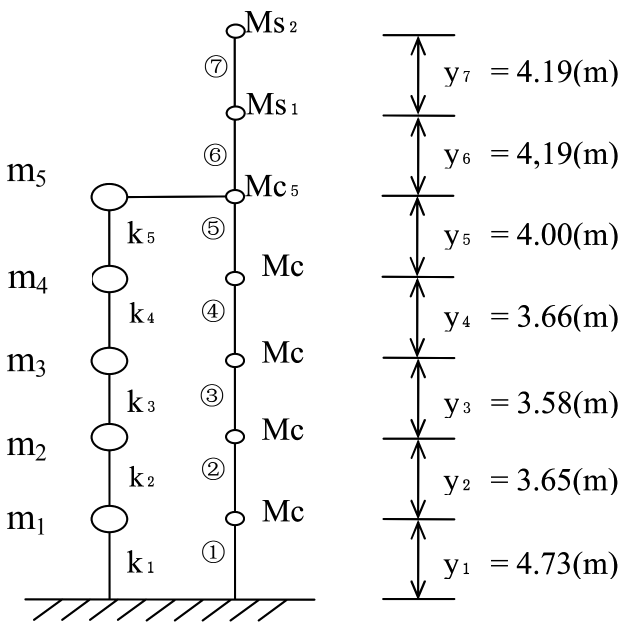

Figure 11: Analysis model for seismic response analysis

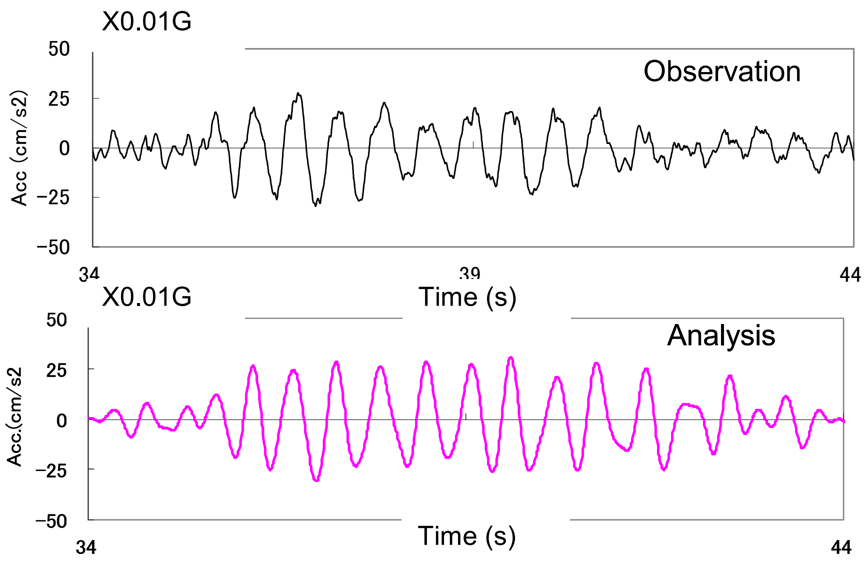

Figure 12: Comparison of wave form by analysis and observation at the top (LT)

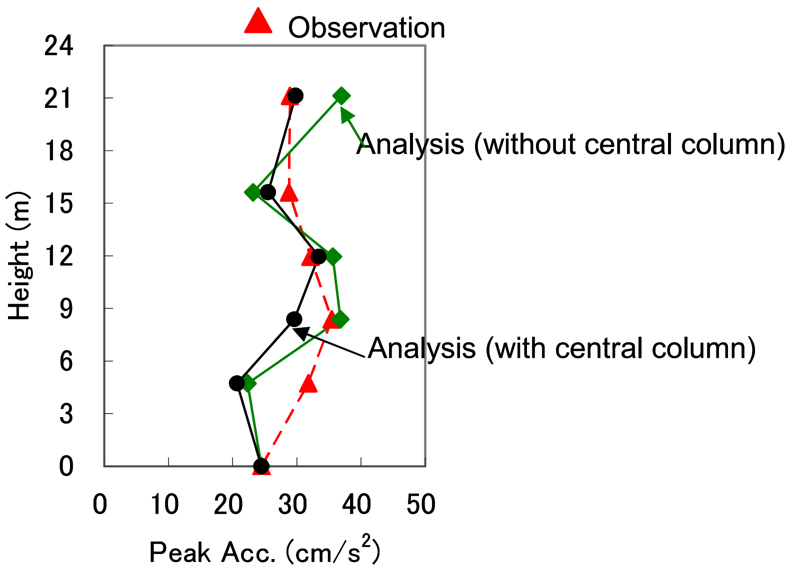

Figure 13: Comparison of analysis and observation of maximum response acceleration

Wind Monitoring

Dynamic actions to the timber heritage structure are produced not only by earthquakes but also by winds. In particular, tall timber buildings such as multi-storied pagodas are affected by strong wind caused by severe typhoons, as the experience shown in Photo 2. As is well known, wind response of structures can be characterized by the behaviours due to not only dynamic response but also wind loading with much longer period. In the present study, a new technology, the image processing system using optical instruments, developed by one of the authors, Niitsu,Y. was introduced to measure exactly the displacement with much longer period. The image processing system consists of CCD cameras, LED makers, and a data acquisition computer. Fig.12 outlines the system installed for the present wind monitoring at the five-storied pagoda in Hokekyo-ji Temple. Shown in Fig.14, a couple of an anemoscope and an anemometer of an ultra sonic type equipment were also installed on the pole (13m high) that stood 15m from the pagoda.

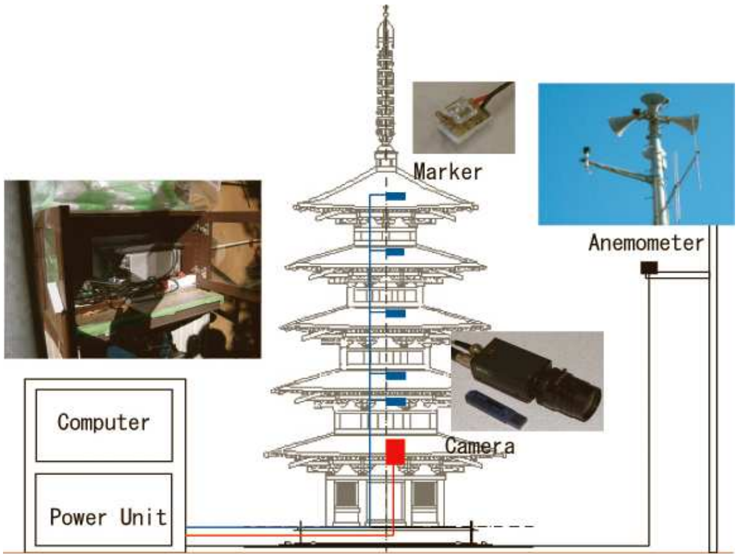

Figure 14: Monitoring system of wind response displacement with anemometer

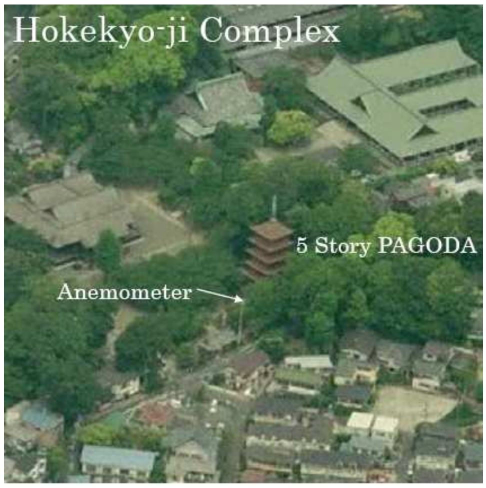

Photo 6: Hokekyo-ji Complex

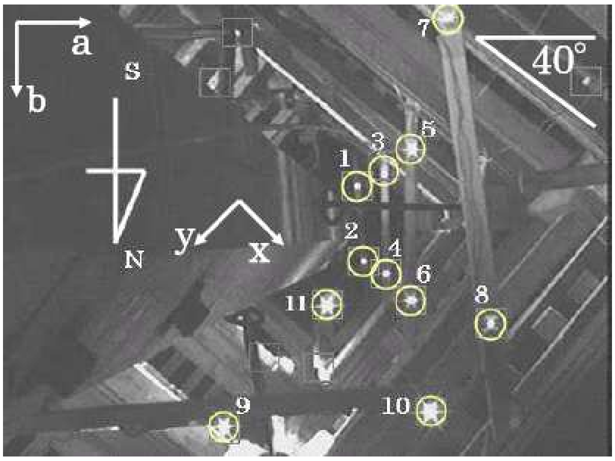

Photo 7: Captured LED markers inside the pagoda

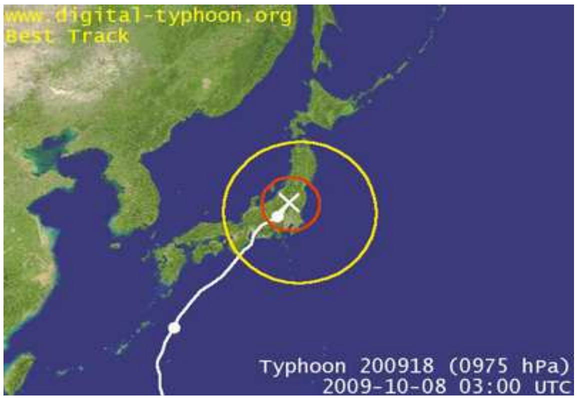

Figure15: Path of the Typhoon Melor, 2010 (National Institute of Information, http://agora.ex.nii.ac.jp/digital-typhoon/news/2009/TC0918/)

It should be considered that wind force is affected by surrounding conditions such as trees, buildings and topography. Photo 6 describes the overall view of the pagoda, in which the pole was also shown. Shown in Fig.14, a CCD camera was placed on the beam at the floor level of 2nd story, being the reference point for relative displacement. Furthermore, LED markers were installed at the level of each story from 2nd story to 5th story, and on the central column. Photo.7 shows the captured multiple markers image and the coordinating system of X,Y and NS,EW. Each marker position in camera image was calculated in the data acquisition PC at the site, shown in Fig.14. Continuous monitoring of the data acquisition has been also conducted with sampling interval of 0.1s (10Hz) for the camera system and 0.25s (4Hz) for the anemometer since April 2009. Shown in Fig.15, Japan mainland was affected by the Typhoon Malor (No.18) in October 8. In this figure, the storm zone defined by the area where the mean wind speed of 10-minutes average exceeded 25m/s is described by a red circle. The anemometer record indicated that the temple had been within this storm zone from around 8 o'clock to noon on October 8. Fig. 16 describes the time history of both the wind direction and speed recorded while the temple suffered the Typhoon Melor. It can be found in Fig.16 that the maximum instantaneous wind speed was 27m/s and that the wind direction showed almost constant (the south wind). Fig.17 shows the time history of the relative displacement at the roof of 5th story, at the 4th story and the central column from the reference point at the floor level of 2nd story.

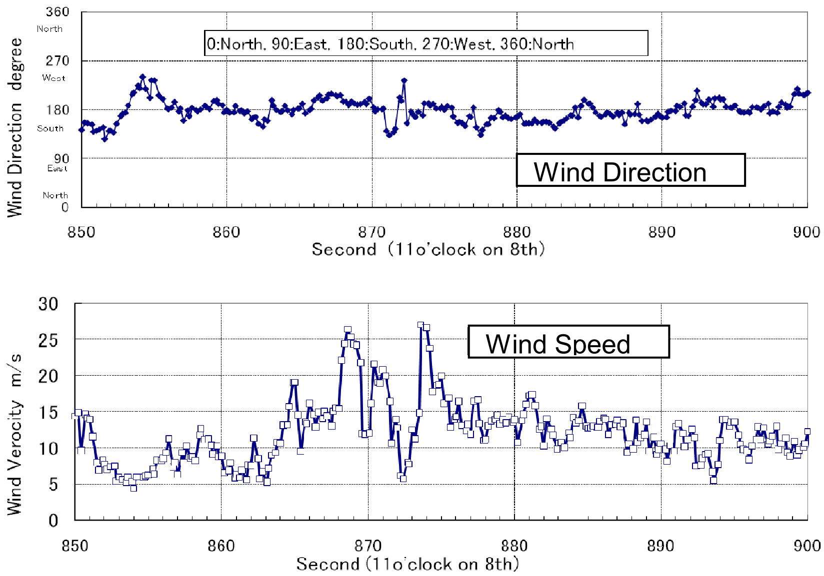

Figure 16: Wind direction and speed recorded when the Typhoon Melor hit

This figure also gives the shapes of the deformation of the main frame structure at the time of the peak responses (a),(b) and (c). As described in Fig.17, the deformation of the main frame structure showed smooth without any irregularity along its height. At the same time, it indicated that the shape could be expressed by combination of the displacement caused by the static wind loading with the one by the dynamic component of 1st mode response. The peak period of the Fourier spectra of the time history of the structural response was approximately 1.3s (See Fig.18). Note that the gust factor is defined as the ratio of the maximum gust speed within a specified period to the mean wind speed. In general, this factor is based on 10-minites mean wind speed. For assessment of the wind performance, such factor of the ratio of the peal value to the mean value is essential. In the present study, we dealt with the ratio of the peak relative displacement to the mean one of 10-minute average. To show this factor, the variation with the time of the peak displacement at the roof (relative displacement from the 2nd story) and the mean one (10-minutes average) is presented in Fig.19 of which coordinate axis was converted to the wind direction (the south-direction). The ratio was evaluated to be 3.3 at the peak relative displacement of approximately 50mm. This monitoring result demonstrated that the maximum story drift of the main frame was as small as 1/290 even when it was affected by the most severe wind force (the maximum wind speed of 27m/s) Such small story drift recorded during the period affected by the severe typhoon indicated good wind performance of the traditional timber pagoda. If the system is assumed to be linear, when the pagoda is subjected to the strong wind of speed of 54m/s (2 times as the observed wind speed), the story drift of the main frame would be 1/72. This story drift is enough within safety level of such traditional timber structures, indicating the structural safety of a five- storied timber pagoda against strong wind.

When a tall building is affected to strong wind, the fluttering phenomenon, if it occurs, causes vibration perpendicular to the wind direction and produces rotational force, which makes the structure instable. In the present monitoring, it should be needed to investigate whether the fluttering phenomenon is caused or not. Fig.20 shows the orbit of displacement at the monitoring point of the roof at 5th story, in which the direction of the wind is drawn. It can be recognized in this figure that no remarkable movement perpendicular to the wind direction occurred, indicating that fluttering was not caused. This may be another reason why the traditional five-storied timber pagodas in Japan (except the case of Shitenno-ji Temple shown in Photo.2) have survived against severe typhoons for centuries. However, further monitoring records is needed to confirm the above mentioned discussions when it is affected by the more severe wind.

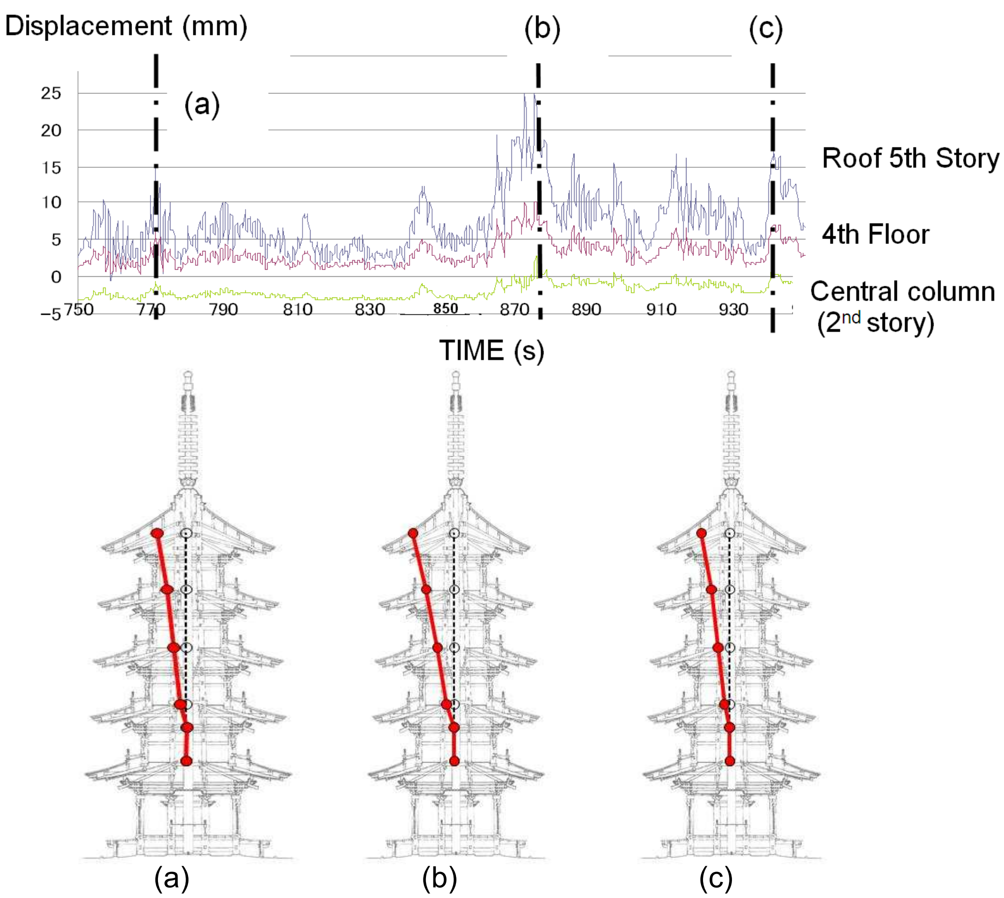

Figure 17: Time history of relative displacement at roof, 4th story and central column from 2nd story, and deformation of main frame at the peak displacement (a),(b) and (c)

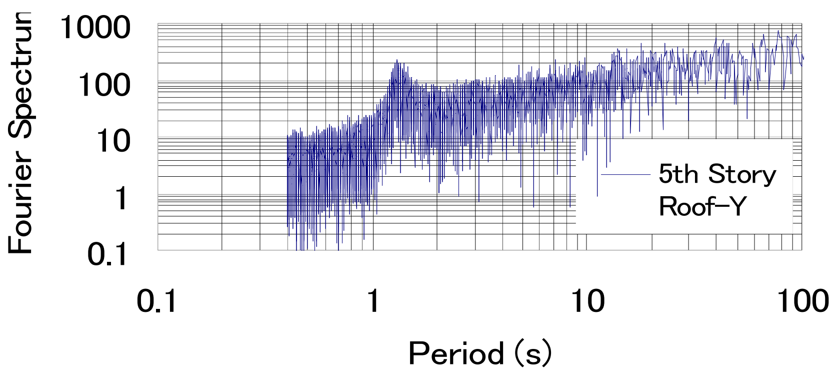

Fig.18 Fourier Spectra of monitoring record at roof of 5th story

Long Term Monitoring of Deformation

Historical timber structures are, in general, likely to be affected by creep phenomenon or by deterioration, and often they suffer serious deformation of the structure. In the present study, the long term monitoring of the horizontal deformation of the main frame has been successfully conducted. Fig.21 shows the variation of the horizontal relative displacement at the roof monitoring point from the 2nd story during the period for 5 months between 29th May and 10th October in 2009. It can be noticed that, while Y-component displacement might be stable, X-component varied with days. This interesting variation of the horizontal displacement in X-direction might be caused by the humidity, as the volume of timber materials is affected by the humidity. However, although it is necessary to

verify the reliability of the monitoring record for long term, further study should be also needed to interpret such long term variation of the structural deformation of interest. During the period for 5 months, two moderate earthquakes occurred on 9th and 11th August in 2009, but neither significant variation of displacement nor residual displacement were caused by these earthquakes, shown in Fig. 21 On the other hand, it can be noticed that the Typhoon Malor affected the history of the horizontal displacement in both X and Y directions on 8th October.

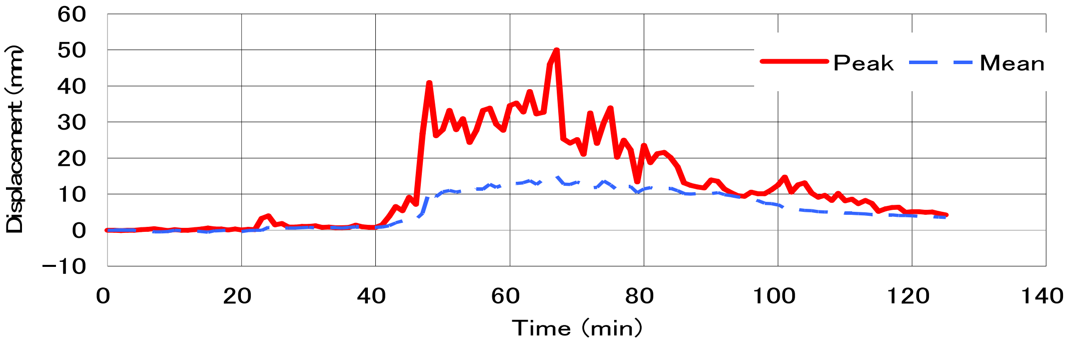

Figure 19: Peak and mean relative displacement at the roof of 5th story in the direction of wind (10 minutes-average)

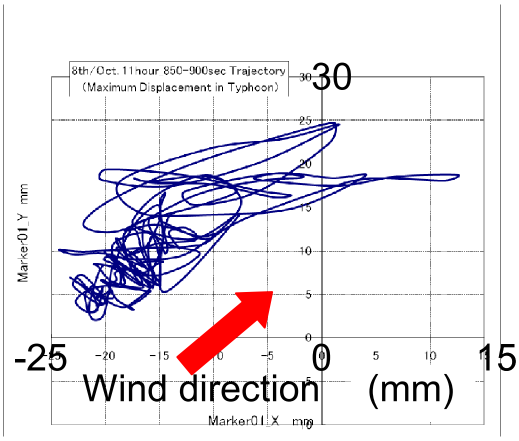

Figure 20: Displacement orbit at 5th story during the period shown in Fig.15

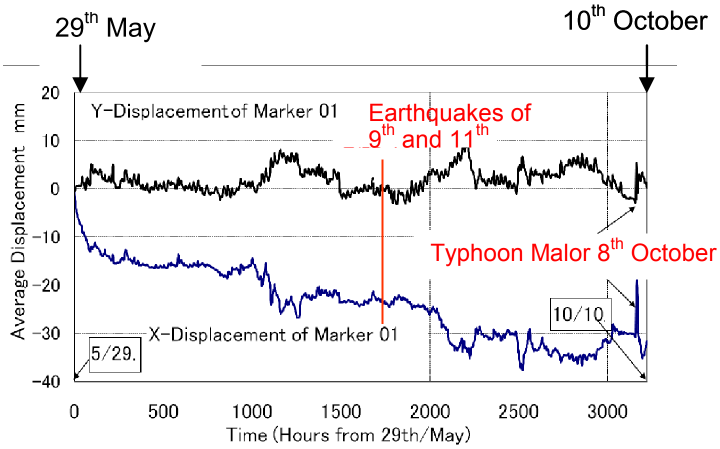

Figure 21: Horizontal displacement variation in X and Y directions at the roof of 5th story from May 29 to October 10, 2009

Concluding Remarks

The outcomes of the present study that has been successfully conducted by the multi-disciplinary team can be outlined as ;

1. There is neither historical document nor record describing that the five-storied timber pagodas in Japan were destroyed by large earthquakes. This experience indicates their excellent and inherent potentialities against earthquakes. A number of studies on this subject have been performed for a century by Japanese famous researchers. On the other hand, structural safety of a five-storied timber pagoda may be affected by strong wind. In the present study, the past studies that have been conducted for a century on seismic and wind performance of the five-storied timber pagodas in Japan was introduced to summarize them.

2. Microtremore measurement must be a useful technique to investigate the fundamental characteristics such as natural period and damping factor. The measurements of the five-storied timber pagodas were conducted at a total of 7 sites to complete a database of the fundamental characteristics of the pagodas constructed before the middle of 19 century and registered as the cultural properties by Japanese government. The empirical equation of the fundamental natural period and the height was derived statistically.

3. Earthquake monitoring using seismograms has been conducted at the five-storied pagoda in Hokekyo-ji Temple, which was constructed in 1622 and has survived against large earthquakes for 4 centuries. Several data of moderate and minor earthquakes have been recorded since April 2007. Strain-dependent (non-linear) characteristics that made the natural period longer as the displacement level became larger were shown. Seismic response analysis using the simplified lumped masses model of which stiffness were determined by the identification was successfully conducted. Further study to record the response to more severe earthquake ground motions will be needed to understand clearly their excellent earthquake resistant capacity.

4. The five-storied pagoda in Hokekyo-ji Temple has also withstood severe typhoons for 4 centuries. In the present study, wind monitoring has been also conducted since April 2008. As it was needed to record time history of displacement composing of longer period component due to wind loading and dynamic component caused by structural response, a new technology was introduced in the present study. To directly measure and record the behaviours of the main frame and the central column, the image processing system using CCD cameras, LED markers and data acquisition PC was developed as a new technology. An anemometer was also installed to observe the wind conditions of speed and direction at the site. Structural response due to the Typhoon Malor that caused the maximum instantaneous wind speed of 27m/s was successfully recorded together with the wind conditions. It was confirmed from the record that the structural behaviours were given by combination of the static component (this term can be rather exactly expressed by "much longer period component") and the dynamic response. The maximum relative displacement at the roof from the reference point at 2^{nd} story was as small as 50mm in the wind direction. This maximum displacement was corresponding to the story drift of 1/290, indicating the safety of the five-storied pagoda against strong wind. The ratio of the maximum displacement to the mean one of 10-minutes average was evaluated to be 3.3. The distribution of the story drift along the height showed smooth without any irregularities. No fluttering phenomenon was shown during the period affected by the typhoon. Those characteristics specific to high rise buildings also indicate the wind safety. To fully understand its wind resistant capacity, however, further study should be needed to record the structural behaviours when it is affected by the more severe wind.

5. Long term monitoring of the horizontal displacement of the main frame has been conducted for 5 months by the image processing system introduced for the wind monitoring as well. An interesting phenomenon was found in the long term variation of the displacement. Although it is necessary to verify the reliability of the monitoring record for long term, further study should be also needed to interpret such long term variation of the structural deformation.

Acknowledgement

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