Performance Evaluation for Traditional Japanese Wooden Pagodas based on Micro-tremor Measurement and Numerical Frame Model Analysis

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SUMMARY:
Anti-seismic efficiencies of Japanese traditional wooden pagodas, a multi-stories timber tower structures, are investigated. Firstly, dynamic vibration properties of existing two 3-stories wooden pagodas were evaluated through micro-tremors measurements. Natural periods and vibrating modal shapes of those ancient pagodas are estimated with FFT analyses. Secondly, two-dimensional multi-members frame models to reproduce and analyze dynamic behaviours of those practical structures are formulated under considering structural mechanism and elements configuration. By Eigen value analyses in elastic region, adequate quantities of every structural element to compose multi-flame numerical model are identified. As following to those parametric tuning procedure, seismic behaviours of those wooden pagodas are investigated through numerical case studies. Through those numerical studies, ant-seismic properties and mechanisms of wooden pagodas are estimated. Especially, contribution in the meaning of the response control by the typical structural column element which is ordinarily located at the core part of the pagodas is focused and investigated.

Keywords: Micro-tremor measurement, System identification, Anti-seismic mechanism, Wooden pagoda

1. INTRODUCTIONS

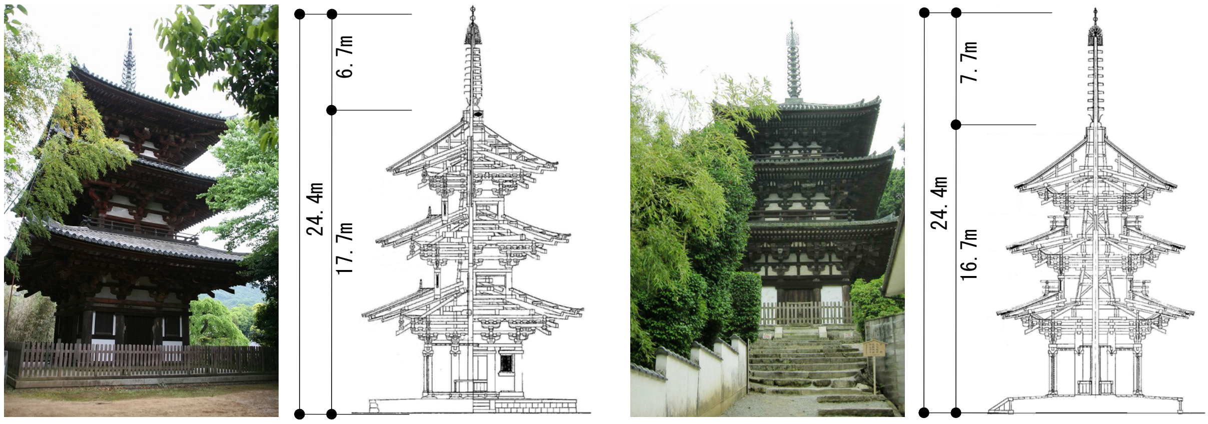
Structural mechanisms and dynamic response characteristics of Japanese wooden pagodas, multi-stories timber tower structures built with the traditional Japanese constructing ways, have not been well-known quantitatively. Accordingly, anti-seismic efficiencies of those tower structures have not been analyzed enough. As the first step of researching procedure in this study, micro-tremor measurements are carried out for two practical 3-stories wooden pagodas built in around 8th and 9th centuries in Nara, Japan and vibrating characteristics of those existing 3-stories wooden pagodas were evaluated through practical observations. Natural periods and vibrating modal shapes of those ancient pagodas are estimated from those micro-level vibrating data via FFT analyses.

On this paper, through estimating for difference and similarity of those two pagodas, emphases are put on identifying distinctive features on dynamic mechanical properties of the wooden pagodas and assuring for common features on seismic behaviors of the wooden pagodas. Two-dimensional multi-frame models are formulated to reproduce and analyze dynamic behaviors of those practical structures. Parametric surveys to identify structural properties on the numerical frame model with Eigen value analyses in elastic region are carried out and adequate quantities of every structural element to compose multi-members flame models of those pagodas are searched out.

As the further approach to evaluate for seismic response characteristics of those wooden pagodas, numerical case studies are carried out. For this aim, seismic responses of the identified multi-frame models and the estimative models to simulate modified structures by changing partial structural parameters from original models are compared and investigated.

2. PAGODA CASE STUDY

Practically existing wooden pagodas are appointed as evaluating studies of this research. Two practical 3-stories Japanese traditional wooden pagodas are investigated with micro-tremor measurements, those pagodas are existed in the same precinct of one of the traditional ancient temple, in Nara, Japan. Those pagodas are sibling structures which are respectively called "East tower" and "West tower", and reported to be constructed at the late of 8th century (East tower; call as Tower-1 in the following) and the beginnings of 9th century (West tower; call as Tower-2 in the following). Over view and sectional view of those pagodas are shown in Figures 1. Whole heights at the tower top-level of both pagodas are 24.4m (include the height of 'Sorin', the symbolic ornament located on steeple top), height of the ridge of the top roofs are 17.7m (Tower-1) and 16.7m (Tower-2), respectively. Building area of the 1st floors are 28.3m^2 (Tower-1) and 27.4m^2 (Tower-2), respectively. Surface of roofs in those pagodas are covered with Japanese traditional tile-roofing. Those pagodas are originally established in the close term each other, and scale and exterior specifications are very similar between those two pagodas. On the other hand, since structural components and constructing style are slightly different between them, structural mechanism could be also different between those two pagodas.



(a) East tower (Tower-1) (b) West tower (Tower-2)

Figure 1. Outlook of researching target pagodas

Feature of constructing style of those pagodas could be pointed that the single core-column of balloon framing (which is called as "Shin-bashira" in traditional name) are getting up on the foundation stones at their basement level as seen in Figures 1. As the common feature of the constructing way of the Japanese traditional pagodas, the core-column is not connected to the main frame structure (which is called as "To-shin" in traditional name) of the tower at any middle part of the core-column. In general, only the top and the bottom of the core-column are connected to the ridge of the top roof and the basement of the main frame structure, respectively. The part of main frame structure ("To-shin") are adopted the superposition layer style which are piled up their story toward to the top as the structural form in both pagodas. Those styles are typical way of construction which was used in the early stage of development of Japanese wooden pagodas (in more recent years, the beam-column frame structural style are developed and adopted in the Japanese wooden pagodas). While precise history of overhaul repairs were not exactly recorded from establishments of those pagodas, as the latest maintenance of those pagodas are carried out in about 150 years ago at the Tower-1 and in about 100 years ago at the Tower-2.

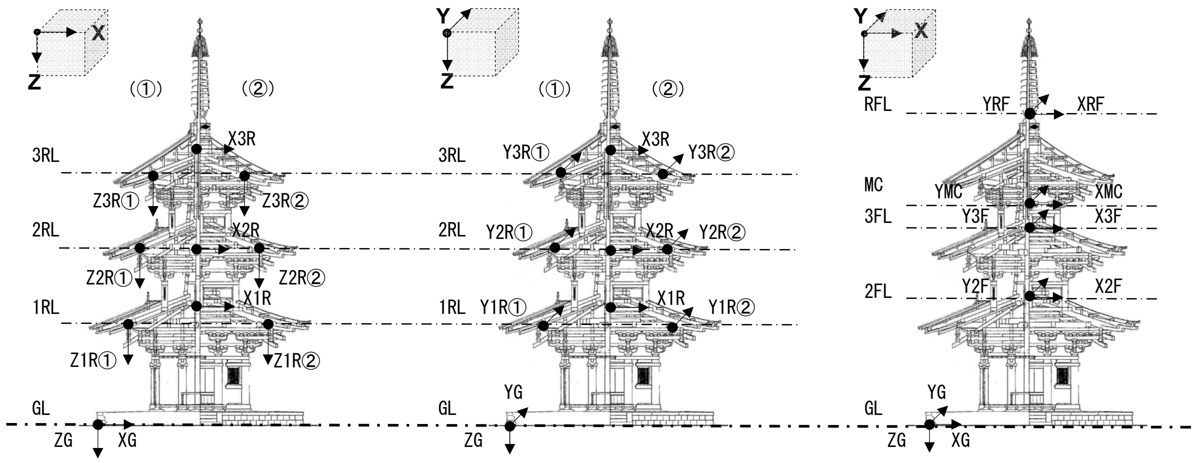
3. MICRO-TREMOR MEARSURMENTS

3.1. Sensor Allocations and Measuring Condition of Micro-tremors

At first, through observations of micro-tremor measurements, practical vibration properties of those existing 3-story wooden pagodas are evaluated to consider dynamic constructing mechanism of those structures. To measure micro-level vibration of those structures, servo-type velocity sensors are used (VSE-15D1, made by Tokyo Sokushin Co.). 11ch of the sensors are prepared for those micro-tremor measurements. Observations are operated for 3 patterns of allocations of the sensors. Those allocation patterns are shown in Figures 2.

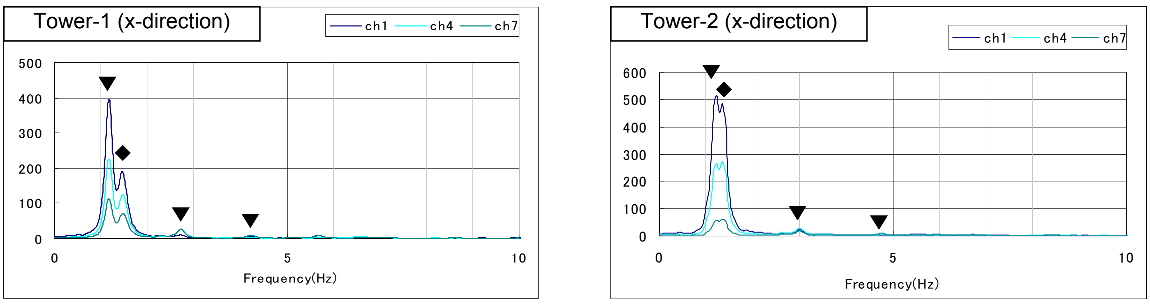
1) Case 1: Setting to observe vertical vibrations at every roof according to the bending motion of the towers along vertical axis (see in Figure 2(a)),
2) Case 2: Setting to observe rotating vibrations at every floor of the main structure according to the twisting motion of the tower in the horizontal plane (see in Figure 2(b)),
3) Case 3: Setting to observe difference of vibration between the main structure and the core-column at every floor level in bi-directions (see in Figure 2(c)).

Recording data are sampled by every 0.01 seconds (100Hz sampling) and sets of 20000 data are gotten by every event (200 seconds). 3 or 4 events are observed by every case.



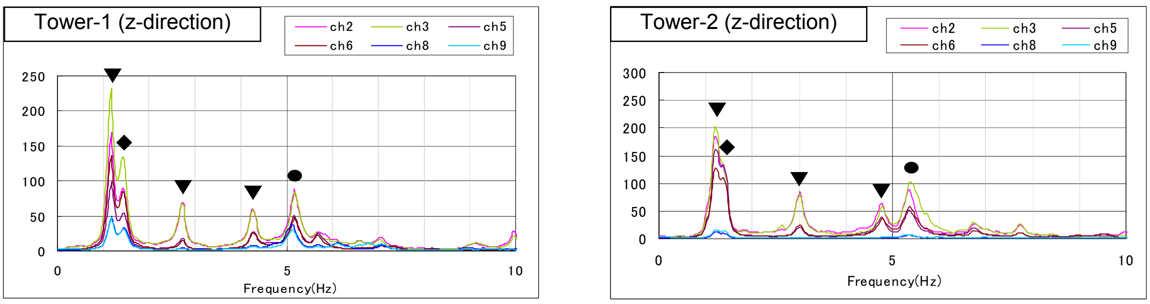
(a) Case 1 (b) Case 2 (c) Case 3

Figure 2. Pattern of allocation of the velocity sensors



(a) Tower-1 (observed at Case 1) (b) Tower-2 (observed at Case 1)

Figure 3. Fourier spectrum of velocity amplitude (ratio to ground velocity) : X-direction



(a) Tower-1 (observed at Case 1) (b) Tower-2 (observed at Case 1)

Figure 4. Fourier spectrum of velocity amplitude (ratio to ground velocity) : Z-direction

3.2. Evaluation of Natural Periods and Modal Vibration Shapes

Observing data via micro-tremors are evaluated through FFT analyses, and Fourier spectrum ratio of velocity amplitude between each investigating point and ground are calculated. Fourier spectrum are transformed from 4096 data in time-domain and every clipping 4096 data are filtered in 8 times by Hanning window in frequency-domain. In each case, plural number of Fourier spectrum to generate by different clipping in observing time-domain data are smoothed by their ensemble average. Diagram of Fourier spectrum ratio in X-direction and Z-direction which are corresponded to the observing pattern Case 1 are shown in Figures 3 and 4, respectively. In those figures, (a) is corresponding to the Tower-1 and (b) is corresponding to the Tower-2. By comparing those figures, some dominant peaks of the spectrum curves can be observed at very similar position in both Tower-1 and Tower-2.

As seen in Figures 3(a) and 4(a), among those peaks, three at 1.2Hz, 2.8Hz, 4.3Hz (as mentioned by the mark '▼') could be regarded as three distinct natural vibrations to relate to sway motions of the Tower-1. Since the peak at 5.2Hz (as mentioned by the mark '●' in Figure 4(a)) are observed only in z-direction, this peak could be regarded to the distinct natural vibrations to relate to vertical motions on the roofs of the Tower-1. On the other hand, the peaks at 1.5Hz (as mentioned by the mark '◆') can be regarded as the vibration correlating to the core-column of the Tower-1, those distinct natural frequencies at the core-column can be also found at 4.7Hz by considering the results of the observing pattern Case 3. As well, by considering the results of the observing pattern Case 2, the peak at 2.3Hz can be found as the distinct natural frequency to relate to rotating motions of the Tower-1 in horizontal plane. In a similar way to observe in Figures 3(b) and 4(b), frequencies of the distinct natural vibrations of the Tower-2 can be found out. Those results are summarized in Table 1.

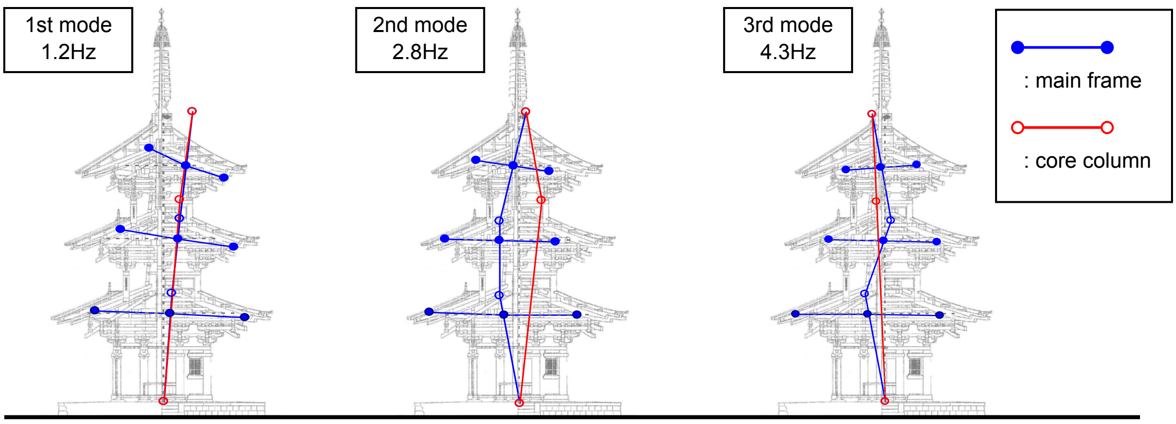


Figure 5. Modal shapes in sway motions identified by micro-tremor measurement (Tower-1)

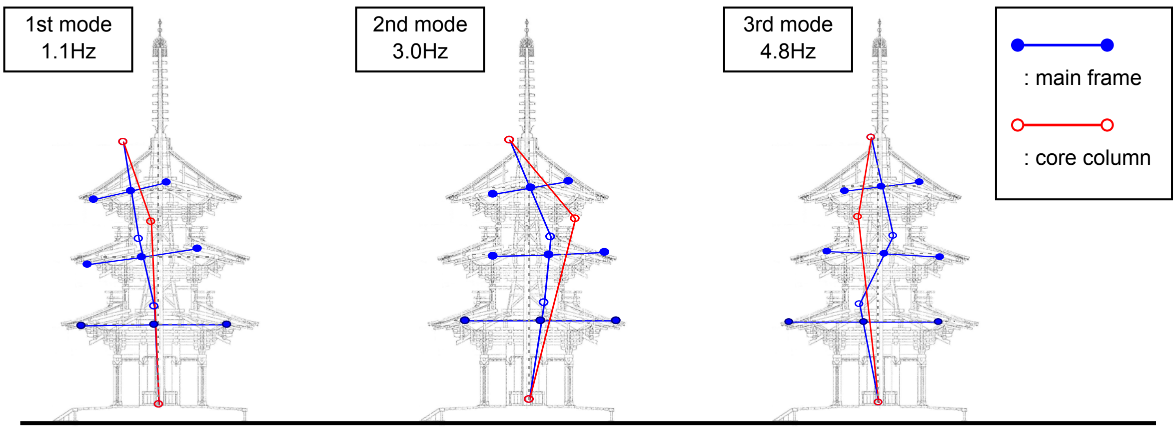


Figure 6. Modal shapes in sway motions identified by micro-tremor measurement (Tower-2)

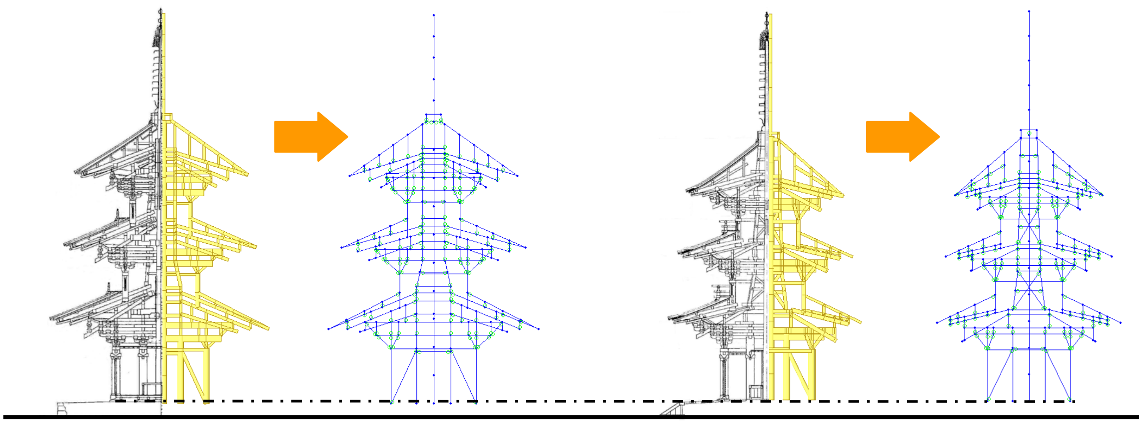
Table 1. Evaluated Natural frequencies according to different vibration mode

Mode [Hz]	Tower-1	Tower-2
Main frame, 1st mode of translation (▼)	1.2	1.1
Main frame, 2nd mode of translation (▼)	2.8	3.0
Main frame, 3rd mode of translation (▼)	4.3	4.8
Main frame, torsion (◆)	2.3	2.8
Core-column	1.5, 4.7	1.4, 2.6
Roof, Up/down (●)	5.2	5.4

For three natural distinct frequencies related to sway motions of the Tower-1 and the Tower-2, corresponding three vibrating modal shapes are evaluated. Those modal shapes are illustrated by considering difference of phase angle between any observing location, evaluated modal shapes are shown in Figures 5 and 6. As seen in those figures, the dominant horizontal sway motions at every story could be subjected by 1st and 2nd modes of natural vibrations of the main structure. The 1st mode is configured by overturning along the vertical axis and the horizontal displacements of the upper floor are generated. The 2nd mode is configured by side-bending at the mid-story and the horizontal displacements of the top floor are suppressed while the mid-stories' deformations are swelling out.

4. TWO-DIMENSIONAL MULTI-FRAME MODEL ANALYSES

To numerically simulate dynamic behaviours of target wooden pagodas, multi-frame models are formulated. Structural elements to characterize mechanisms of those pagodas are carefully extracted, two-dimensional frame models are produced. Numerical modelling and calculations are operated on the general-purpose simulating solver (midas-Gen). Configuration of the frame models are shown in Figures 7.



(a) East tower (Tower-1) (b) West tower (Tower-2)

Figure 7. Two-directional multi-frame models for numerical simulations

Every member is modelled as beam element. Connecting conditions between any elements are considered as fixed node or hinged node, so that the whole of models are assembled by rahmen-shaped sub-frames. In those models, virtual braces at the 1st story are installed to represent equivalent efficiencies with the stiffness of practical soil walls, and truss supports at top of columns in every story are installed to represent equivalent mechanism of the wooden bed block to support girders. Weight of every elements are distributed as lumped mass to their belonging nodes, additionally, weights of roof are externally given as distributing loads on every beam elements corresponding to the rafters. The core-columns are considered only to be connected to the main structure at its top and bottom and only to support the vertical load of 'Sorin' part (the symbolic ornament located on steeple top).

4.1. Parametric Survey via Eigen Value Analyses in Elastic Region

To survey adequate values of the dynamic parameters on the numerical models, iteration to reproduce observed natural periods in sway motions are carried out. Through those procedures, stiffness of the modeling elements are tuning proportionally and dominate three sway modal motions in the numerical models are identified to adequately represent observing results. Modal shapes in sway motions reproduced with numerical models are shown in Figures 8 and 9. By comparing those figures with Figures 5 and 6, it is assured that identified modal shapes have comparatively exact reproducibility by tuning structural parameters proportionally according to the original configurations of the target structures.

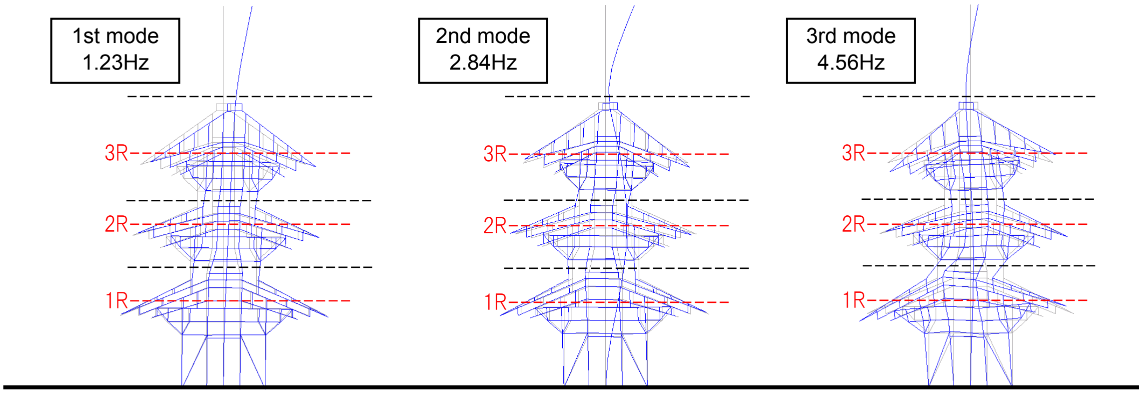


Figure 8. Modal shapes in sway motions reproduced with numerical model (Tower-1)

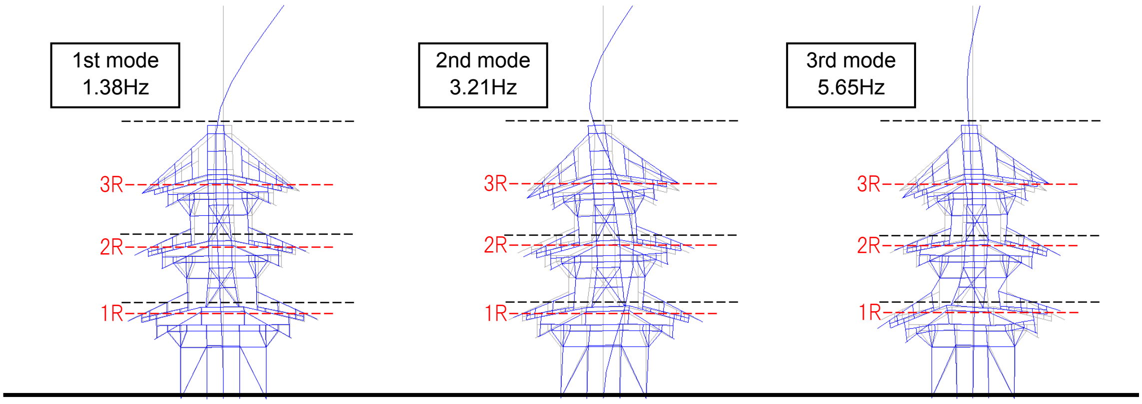


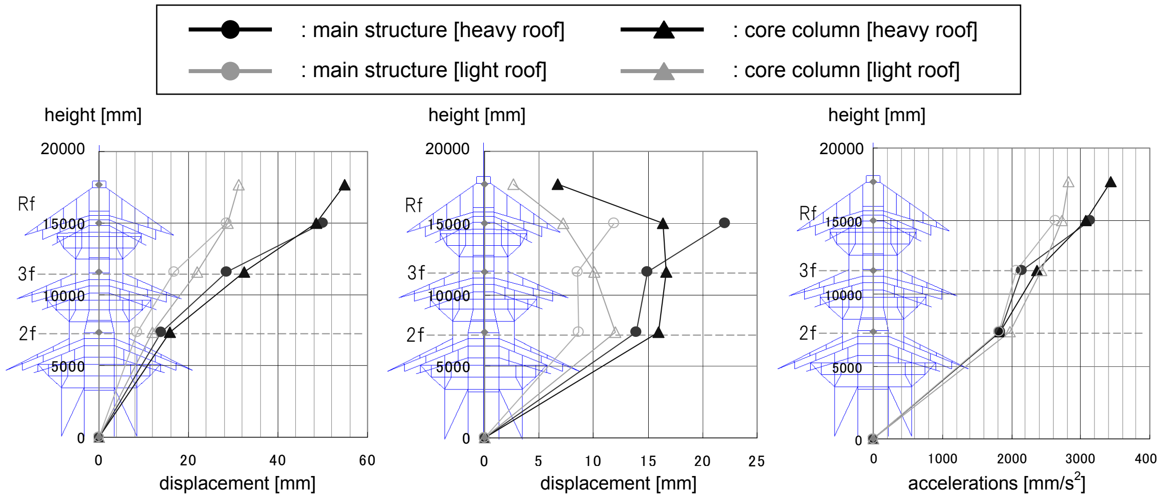
Figure 9. Modal shapes in sway motions reproduced with numerical model (Tower-2)

Table 2. Weight of the Reseach target Pagodas

Model [kN]	1st Story	2nd Story	3rd Story	Total
Tower-1	444.3	354.0	335.2	1133.5
Tower-2	384.4	311.5	318.9	1014.8

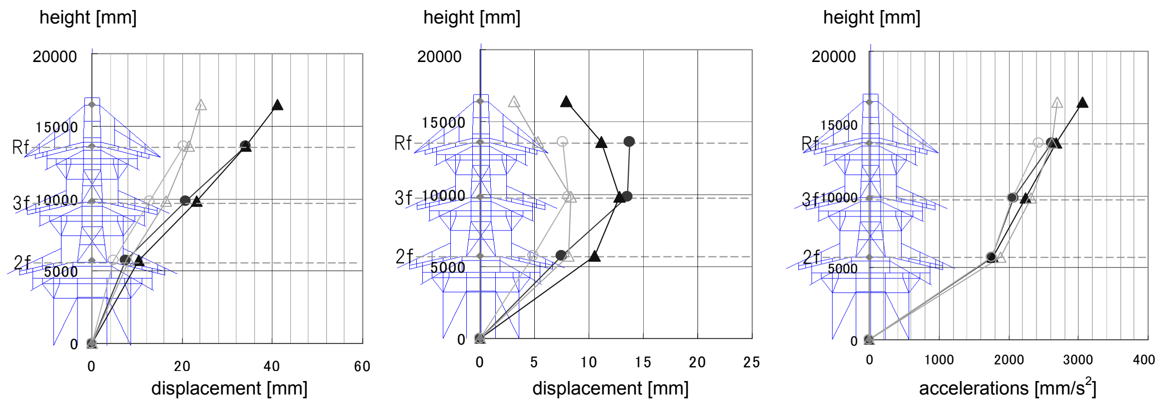
4.2. Case Study on Seismic Response Analyses

To investigate seismic behaviour of the 3-stories pagodas, numerical response simulations by using JMA-Kobe (1995) NS (time duration : 30 seconds) as input motion are carried out. The following case studies are considered in the elastic region of the numerical models, so that the maximum amplitude of the input motion is reduced to 20% for the original records. Two kinds of cases which suppose different weight for each roof are investigated. For both models of the Tower-1 and the Tower-2, the cases of Model-1 (heavy roof) and Model-2 (light roof) are considered. The Model-1 is corresponded to the identified numerical models which are tuned as fitting micro-tremor evaluations on the practical pagodas. The Model-2 is the 'estimative' model which are changed their weight into one half from the Model-1. Damping of the frame models are supposed as proportional type to stiffness matrix and damping ratio h=0.05 for the first modal period is considered. Weights of each story of the identified models of investigating pagodas are described in Table 2.



(a) Horizontal Displacements (b) Story Deformations (c) Accelerations

Figure 10. The maximum responses for seismic analyses (Tower-1)



(a) Horizontal Displacements (b) Story Deformations (c) Accelerations

Figure 11. The maximum responses for seismic analyses (Tower-2)

Figures 10 and 11 show the maximum responses for two kinds of models of the Tower-1 and the Tower-2, respectively. In those figures (a), (b) and (c) are corresponding to the maximum horizontal displacements, story deformations and accelerations, respectively. As seen in Figure 10 (a) and (c), it is assured that the maximum vibrating responses are dominated by the 1st modal shapes of the Tower-1. Horizontal displacements are reduced in the case with reducing roof weight, while accelerations are mostly same at the both models with different weight of roof. On the other hand, story deformations at every story are reduced at the Model-2 with mostly same reduction ratio from the Model-1 at each story (as seen in Figure 10 (b)), namely, story deformations and horizontal displacements of the Model-2 are proportionally decremented by effect of reducing roof weight. By comparing responses of the main structure and the core-column, difference between inter-story deformations of the main structure and the core-column is observed to be large at the 2nd story and to be small at the 3rd story. As seen the 2nd modal shapes of the pagodas in Figures 5 and 8, since the large gaps between inter-story deformations of the main structure and the core-column appear at near the 3rd story, it is considered that the inter-action between those structural systems affect to the response control for modal responses in bending motions. As seen in Figure 11, similar tendencies mentioned above can be also observed in the Tower-2.

By comparing Figures 10 and 11, either of the maximum horizontal displacements, story deformations and accelerations is observed to be smaller in the Tower-2 than the Tower-1. Those differences are markedly exposed in the responses of displacements. As seen in Figure 10 (b), the inter-story deformation at the Rf level in the Tower-1 is enlarged more than others while the response of Rf level in the Tower-2 is the same extent with the 3f level. As one of the reasons for this, it is considered that the weight of the Tower-1 is slightly larger than the Tower-2 and that large and small of bending-back effects by the core-column in those pagodas may affect to those difference between two towers. When roof weights are reduced, decreasing effect for responses of displacements is obviously observed in those case studies (as seen in Figures 10(a) and 11(a), 10(b) and 11(b)). It seems that effects of reducing roof weight can be also related to increase bending-back effects of the core-columns. On the other hand, it is pointed that those factors are not sensitively acting upon the acceleration responses. Effects of reducing roof weight do not notably appear on difference of accelerations.

Table 3. Change of Natural frequencies by Reducing Weight of Roof

Mode [Hz]	Tower-1		Tower-2	
	Model-1	Model-2	Model-1	Model-2
1st mode of sway	1.2	1.5	1.1	1.7
2nd mode of sway	2.8	3.6	3.0	3.9
3rd mode of sway	4.3	5.8	4.8	7.0

5. CONCLUSION

In this paper, results of micro-tremor measurements for two practical 3-stories wooden pagodas are reported. By considering identification of natural vibrating modal shapes of those pagodas via FFT analyses. Two-dimensional multi-frame model are formulated and dynamic behaviours of the wooden pagodas are numerically investigated through seismic case studies. Thorough those numerical studies, the following features are assured:

1) Dominant frequencies and modal shapes of the Tower-1 and Tower-2 can be evaluated as very similar via micro-tremor measurement,
2) Adopting 2D multi-frame models can exactly reproduce modal shapes by tuning structural parameters proportionally according to the original configurations of the target structures,
3) Accelerations responses by the seismic analyses for those two structures have no remarkable difference, and those are dominated by the 1st modal shapes,
4) Difference of displacements responses by the seismic analyses for those two structures markedly appear and effects by changing roof weights affect to reduce displacements.

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