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EXPERIMENTAL AND ANALYTICAL ASSESSMENT OF SEISMIC BEHAVIOR OF A TRADITIONAL JAPANESE WOODEN SHRINE SUPPORTED BY FRICTION

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Abstract

The dynamic response of a traditional Japanese wooden shrine is investigated experimentally by means of a series of shaking table test. Traditional wooden shrines in Japan are in general not fixed to the base and instead of that columns rest on stone bases. Then in case of horizontal loads like earthquakes they are resisted by friction forces developed between bottom part of columns and stone surface of base. First, vibration characteristics of a selected shrine are estimated from ambient vibration measurements and their correspondent Fourier spectrum analysis. Then a reduced scale model was tested on shaking table to investigate its dynamic response when specimen is subjected to pulse wave and sinusoidal wave. To simulate the stone foundation ceramic tiles were used as base considering that selected tile surface has similar characteristics as stone surface. From this shaking table test some equivalent friction coefficient was obtained and it was also verified sliding behavior and in-plant torsion behavior. It is believed that torsion response is due to non-uniform distribution of vertical loads on columns which originates unbalanced friction forces. The equivalent friction coefficient obtained from shaking table test could be used to perform time history response analysis considering friction behavior of base foundation.

Keywords: Traditional wooden structure, shaking table test, seismic behavior, friction support

1. Introduction

Most of heritage architecture buildings, in Japan, are traditional wooden structures. These structures are flexible structure and they present some deterioration of their earthquake resistance characteristics due to aging. Huge traditional structures located at important cities like Kyoto or Nara have good maintenance and preservation works as carried out regularly. However in small cities, local heritage structures are not well studied. Then it is desirable to construct an analytical model to investigate the structural performance of this kind of buildings located at rural areas of Japan. However in these traditional constructions, where nails or other type of devices are not used for connection of columns and beams, modelling of structural joint requires assignation of a rotational stiffness of joint. Moreover, foundations of these buildings are not fixed in ground and bottom part of columns only rest on surface of stone foundation. Therefore the support of these traditional buildings must be modeled as frictional support which makes difficult the structural analysis specially the earthquake response analysis. Then in this study shaking table tests on scaled specimen were performed to investigate its dynamic response considering that model is supported only by friction.

As a preliminary task investigation of existing shrine was performed to determine its dynamic properties like frequency of vibration. Then based of this actual shrine, a scaled test specimen was constructed and subjected to forced vibration test and shaking table test. The inputs for shaking table test were pulse wave and sine wave with variable amplitude. The frequency of input waves was selected from ambient vibration measurements of test specimen, having a value equal to the predominant frequency of the test specimen to obtain a maximum response in near resonance.

2. Selected shrine for ambient vibration measurement.

A typical shrine located at Yurihonjo city in Akita prefecture, Japan was selected to estimate its dynamic properties using ambient vibration measurements. Fig. 1 shows a general view of this shrine and also points of measurements. This shrine that is called the Yashima Hachiman has been declared as an important cultural heritage of Akita Prefecture, Japan. It is said that the shrine was constructed by one of the 12 landlords of Yuri region Mr. Oi, during the first period of Edo era (15th century). The building itself is a small structure however it has a thatched roof that gives it the appearance of a heavy construction. For its architectural characteristics and details, like beams of entrance hall with form of elephant nose, the shrine was declared as an important cultural property in year 1953. Due to its structural condition the shrine has been preliminary reinforced with some external wooden frame located behind the structure. Then studies to estimates its dynamic characteristics are required to establish recommendation for repair and reinforcement of the structures.

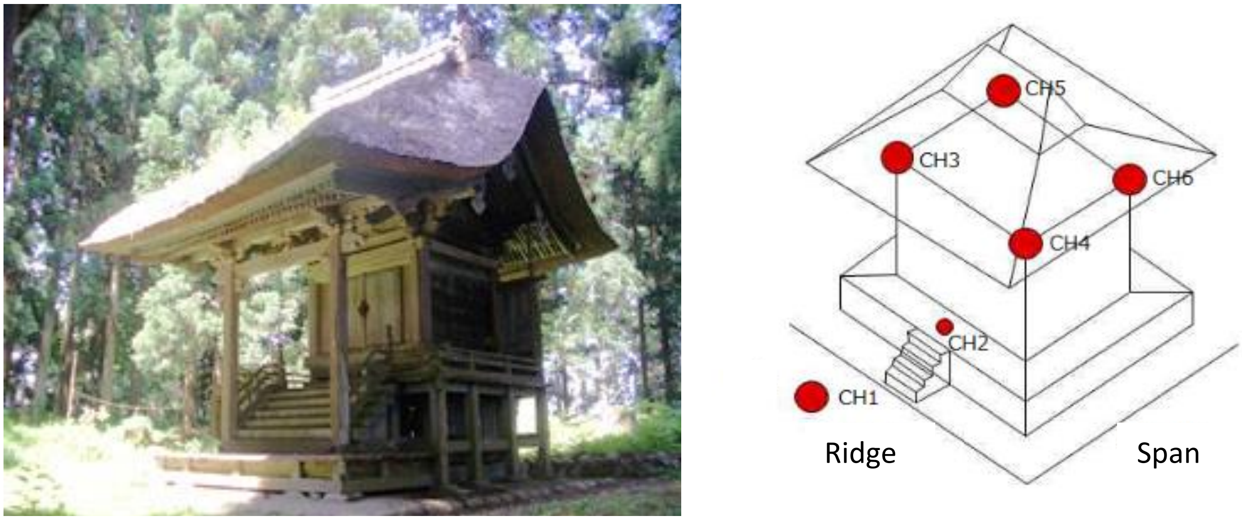


Fig. 1 – Typical shrine and points of ambient vibration measurements

The target structure has been studied since year 2009 to monitor its dynamic properties, specially its period or frequency of vibration. Since wooden structures are flexible structures, it is possible to obtain its predominant frequency from a Fourier spectrum instead of a transfer function. Typical recorded signal is shown in Fig. 2, from where only 40.96 s that corresponds to a stable portion of the record is taken for the Fourier analysis. As illustrative example of Fourier analysis results, Fourier spectrum curves for the two horizontal directions (ridge direction and span direction) are show in Fig. 3.

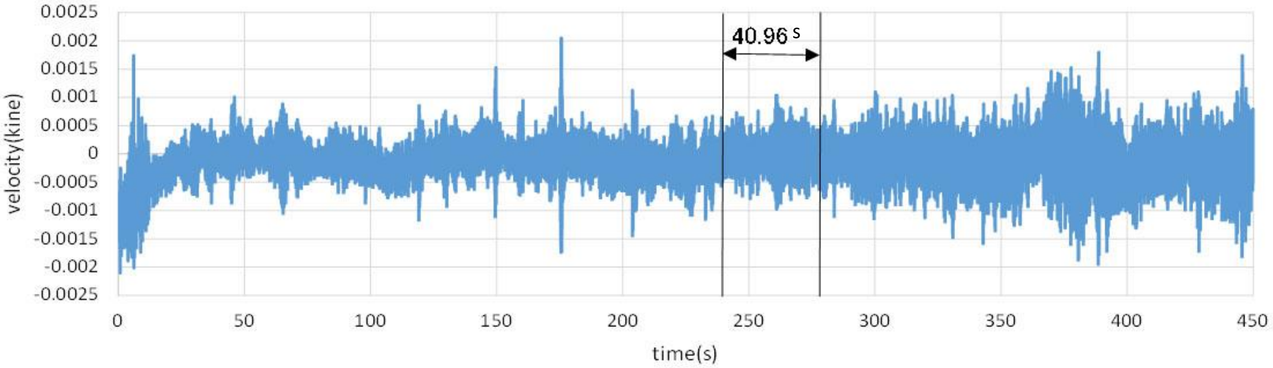


Fig. 2 – Typical ambient vibration record

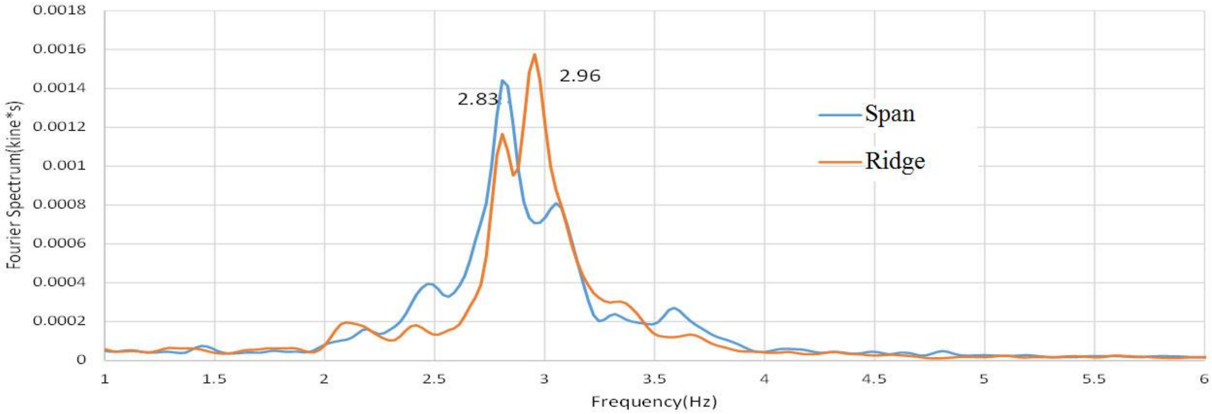


Fig. 3 – Fourier spectrum curves

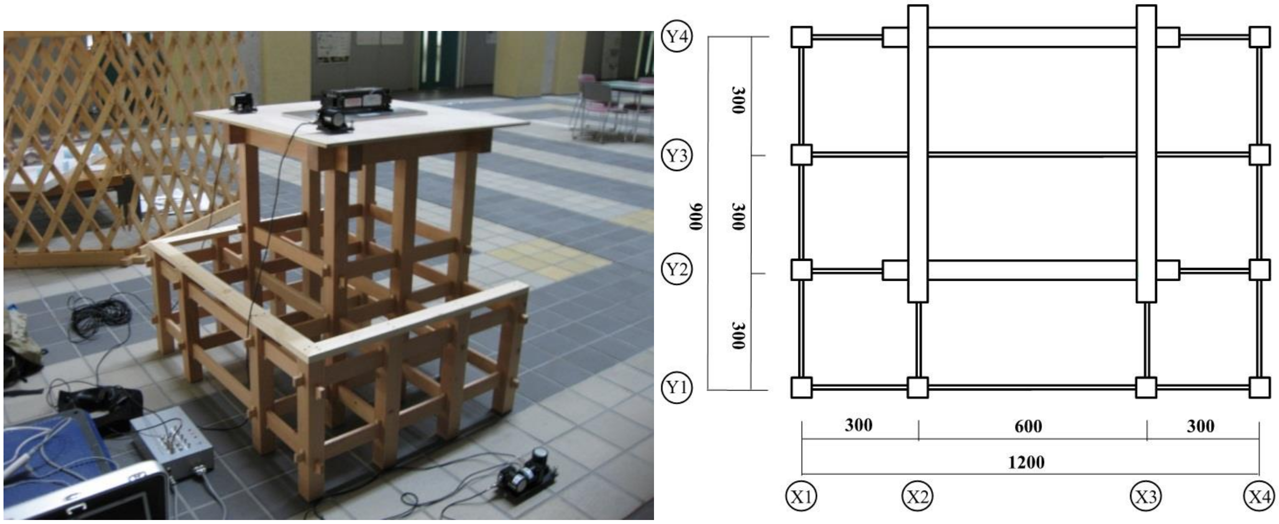
The variation or change in the value of predominant frequency of the target build is shown in Table 1. It can be observed that predominant frequency decreased from 3.83 Hz to 2.96 Hz for span direction, reaching its lowest value in year 2011 at 2.66 Hz. This small recovering in predominant frequency can be explained by the effect of the reinforcing work of the shrine in this direction that was performed in year 2012. In the case of ridge direction decreasing of frequency value was observed from 3.91 Hz to 2.83 Hz.

Table 1 Variation of predominant frequencies for target shrine

Date	Span direction (Hz)	Ridge Direction (Hz)
①2009.08.06	3.83	3.91
②2010.09.29	3.08	3.37
③2011.06.09	2.66	2.91
④2012.05.24	2.76	2.91
⑤2014.06.03	2.96	2.83

3. Specimen and experimental test series

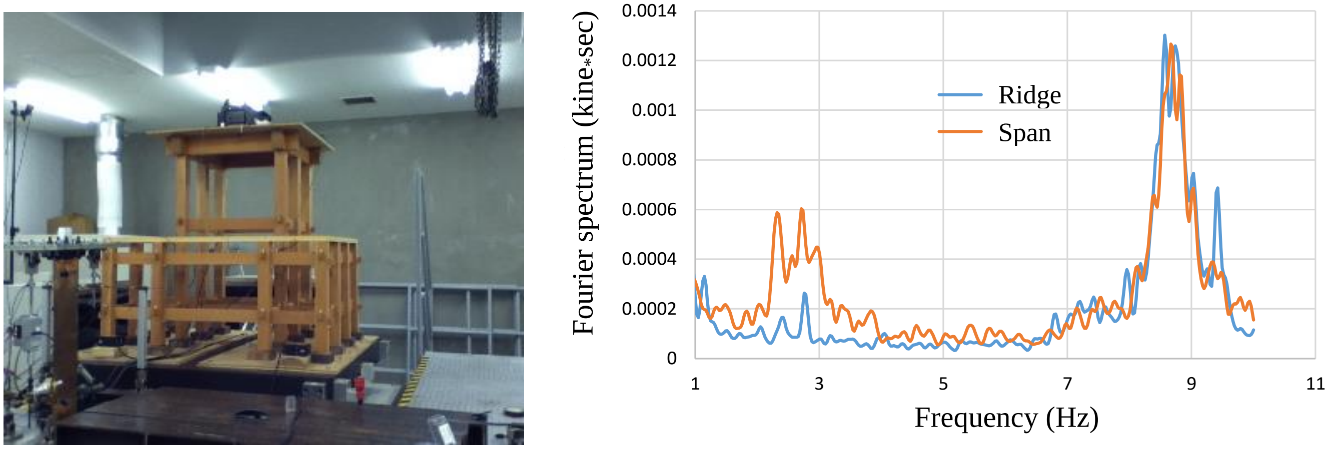
A scaled model that is shown in Fig. 4 was constructed and subjected to pulse waves and harmonic waves on shaking table test. The reduced scale model was planned based on the structure of the traditional shrine that was described previously and that is shown in Fig. 1. The scale factor is approximately 1/5 and only the main structure has been considered. The roof is considered as additional weight to be added to test the prototype. A stiff wood panel was set up at the top of the specimen to simulate the effect of the roof. This panel supports the additional weight that take into account the roof. Plane ceramic tiles were used to simulate base supports since it was considered that its surface presents similar rugosity or same friction characteristics as stone supports. Fig. 4(b) shows the dimensions of test specimen. Fig. 4(a) shows the location of ambient vibration sensor to estimate the predominant frequency of the specimen and also the forced vibration machine. The ambient vibration measurements were performed also after installation of specimen on shaking table.



(a) (b)

Fig. 4 – Ambient vibration measurements and specimen dimensions

Fig. 5 (a) shows the test specimen that is installed on the shaking table test. The ambient vibration measurements were also performed for the test specimen installed on the shaking table to estimate its predominant frequency. Then, by means of a Fourier analysis of the recorded signal predominant frequencies of 8.63 and 8.54 were obtained for span direction and ridge direction respectively. In average these frequencies correspond to a predominant period of 0.12 s. Results of Fourier analysis of ambient vibration records of test specimen are shown in Figure 5(b).



(a) (b)

Fig. 5 – Test specimen on shaking table and Fourier analysis results

The input motions were setup to have a period of 0.12 s to obtain a maximum response of test specimen since resonance is induced. Pulse waves and sinusoidal waves were used as input motions. Response of test specimens were measured with accelerometers located at selected positions. Also to measure the sliding of test specimen laser displacement transducer were setup at bottom of two columns. Locations of accelerometers on specimen are shown in Fig 6.

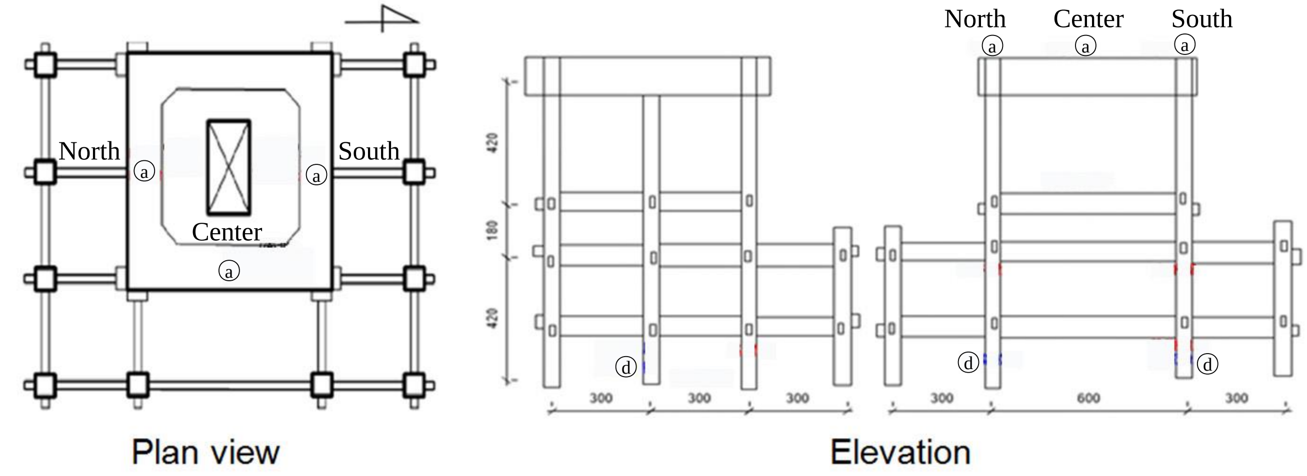


Fig. 6 – Location of accelerometers (ⓐ) and displacement transducers (ⓓ)

Pulse inputs of 800 cm/s^2 of maximum acceleration and 0.06 s of period (0.12 s if complete period is considered) were employed for 5 consecutive runs. Actually each run consisted of one pulse in a positive direction and another pulse in reverse direction.

In addition, sinusoidal wave with a period of 0.12 s and variable amplitude from cero to 800 cm/s^2 was used in 3 runs. Duration of this variable sinusoidal wave was 10 s.

4. Test results

Fig. 7 shows results of acceleration response for pulse wave. This wave was applied consecutively, first in a positive direction and after 5 seconds in a negative direction. Red lines represent specimen response. As it is observed the absolute value of maximum acceleration of pulse wave was 800 cm/s^2.

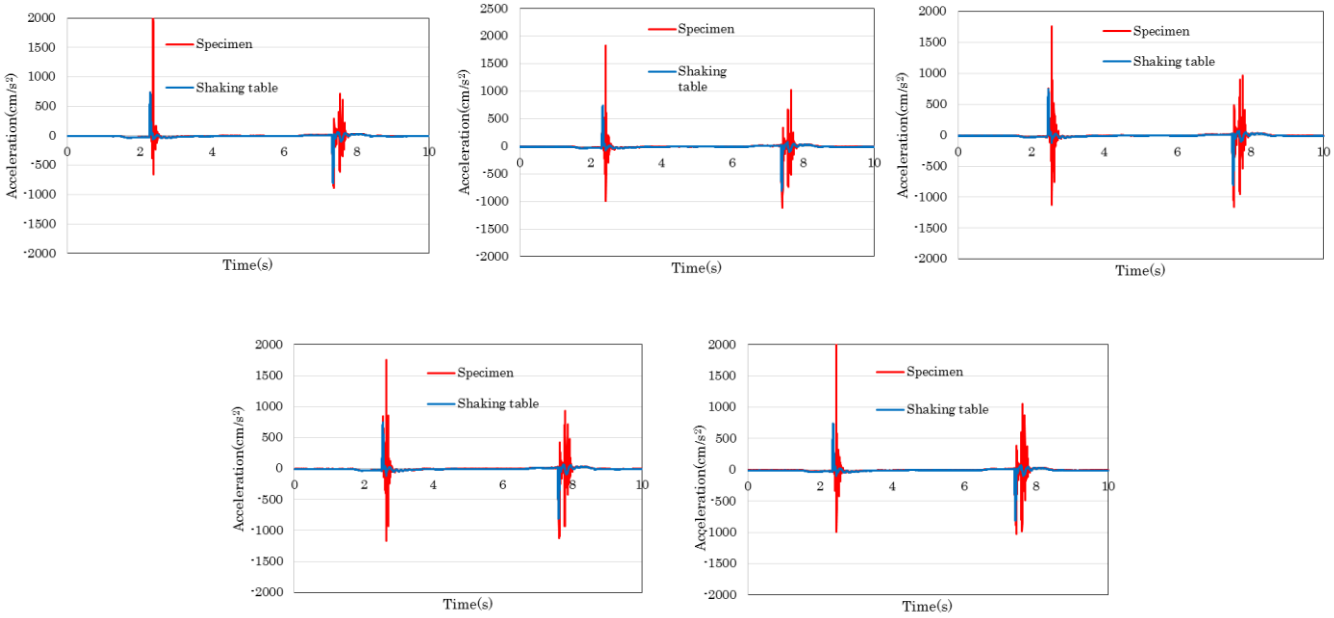


Fig. 7 – Response of prototype to input pulse wave

Using results corresponding to pulse input, some equivalent friction coefficient can be estimated considering that slip occurs when acceleration signals of shaking table and test specimen differ in their path as is shown in detail in Fig. 8. Here initial portion of the signal correspondent to the 4th run is shown. If accelerations of shaking table and test specimen are same there is not slip. Then when curves of acceleration diverge as is show in Fig. 8 at that moment friction force was overcome and from this acceleration friction coefficient can be estimated. Results for equivalent friction coefficient are summarized in Table 2.

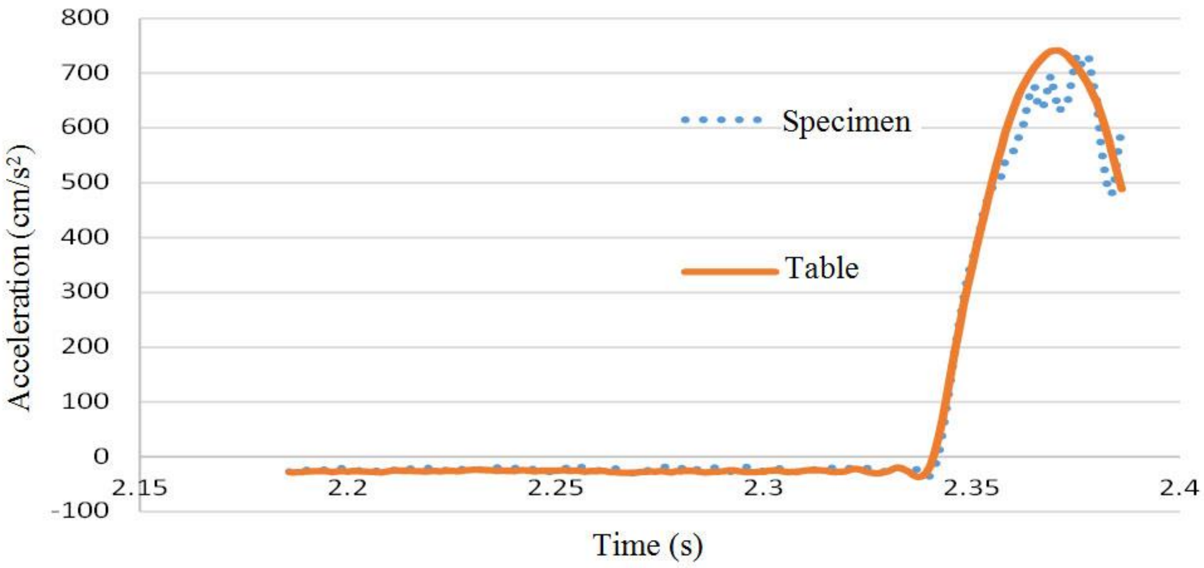


Fig. 8 – Detail of specimen response to pulse wave

Table 2 Equivalent friction coefficients estimated from response to pulse input

Pulse wave	Acceleration at slip (cm/s^2)	Friction coefficient
Run 1	374.53	0.38
Run 2	364.13	0.37
Run 3	326.90	0.33
Run 4	505.06	0.52
Run 5	473.35	0.48

Results for sinusoidal wave input are presented in Fig. 9. In this case as illustrative example signals recorded at top of the specimen are shown. In all cases maximum accelerations observed on test specimen are smaller than maximum input acceleration. At initial portion and at final portion of signals acceleration of top specimen exceeds the input acceleration. This fact means that when specimen is in touch with the base and moves together input acceleration is transmitted and even amplified in test specimen. Then when acceleration reaches a value that produces sliding of specimen, the input acceleration is dissipated by friction and not transmitted completely to the specimen.

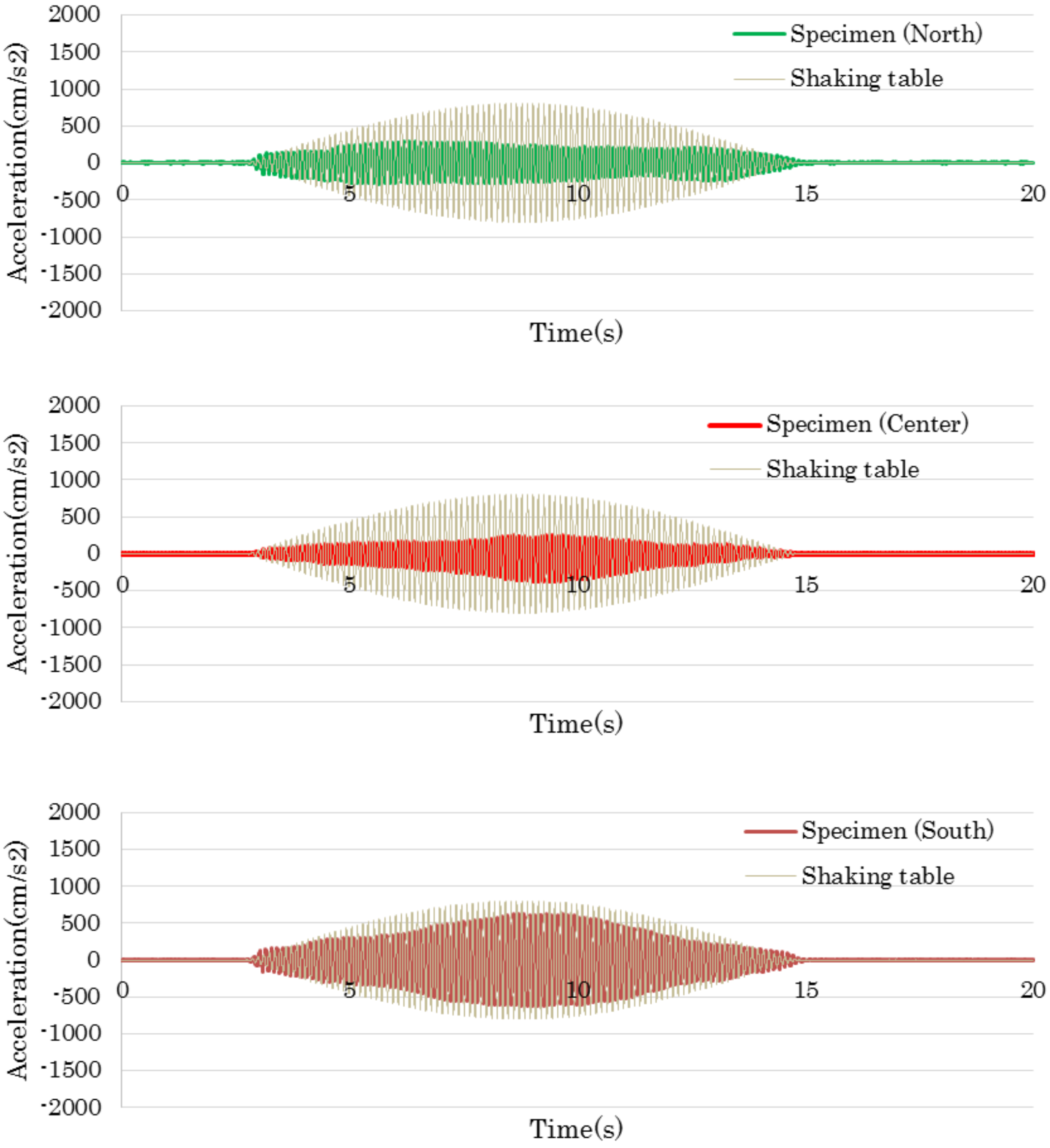


Fig. 9 – Sinusoidal input acceleration and specimen response

In previous research larger acceleration of top specimen in comparison with input acceleration was reported. It is believed that in that case vertical rotation of test specimen induced larger acceleration. This vertical rotation occurred because some columns were not in contact with the base and these clearances permit vertical rotation. In the present research wedges were used at bottom part of columns to ensure that all columns are in contact with the base and therefore the vertical rotation induced by the horizontal action was reduced. However the use of wedges do not ensure a uniform distribution of the specimen weight and therefore frictional forces developed at bottom part of columns are not uniformly distributed and produces a torsion in plan. These movements were verified by mean of laser transducers located at bottom part of columns. Fig. 10 shows the record of these transducers and can be appreciated that sliding of specimen is not parallel since north portion moves in positive direction and south portion moves in negative direction.

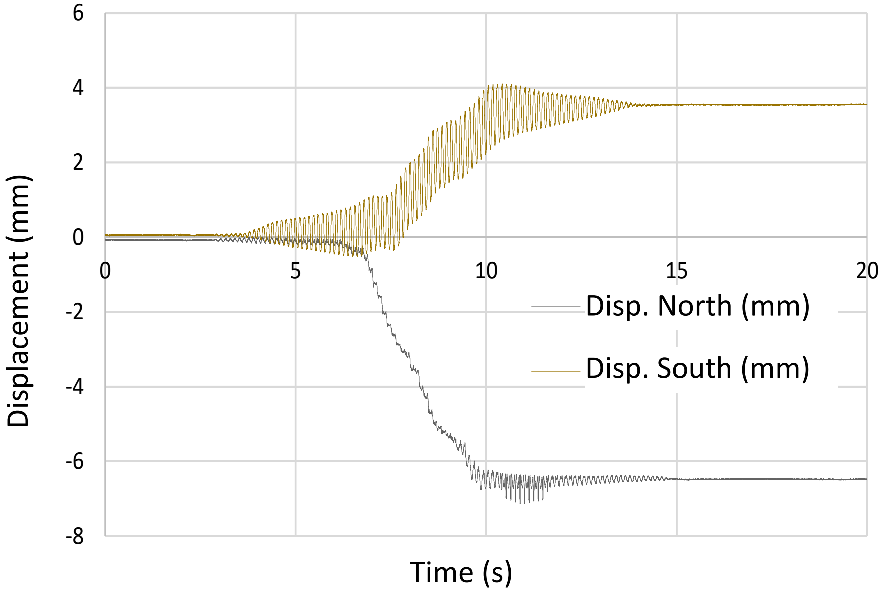


Fig. 10 – Displacement of bottom part of columns

The sliding movement of test specimen describe in previous paragraph is shown schematically in Fig. 11. Here for simplicity a displacement of 6 mm in south direction and 4 mm in north direction are shown.

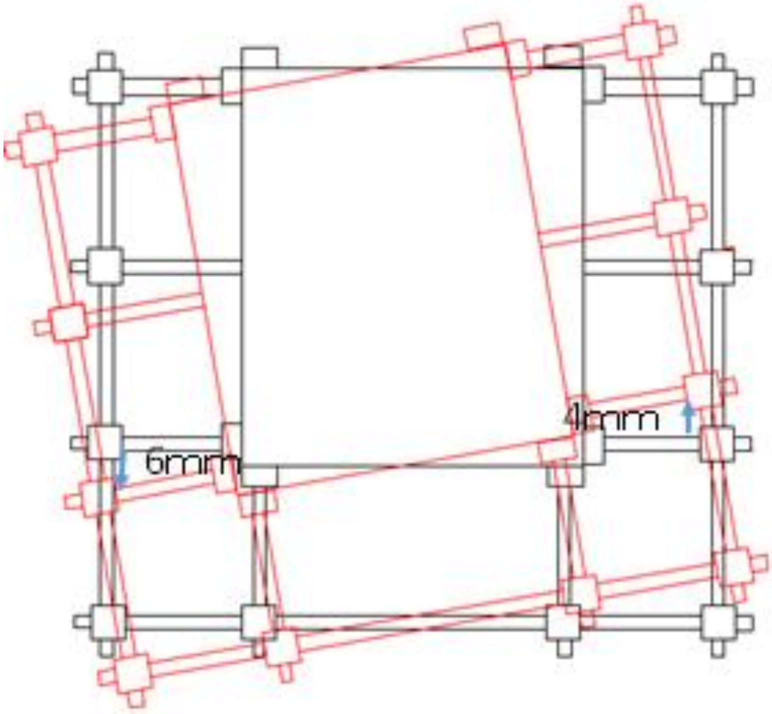


Fig. 11 – Displacement of test specimen showing torsion in plan

5. Conclusions

A typical Japanese wooden shrine was selected to investigate its dynamic properties. Since this kind of structures are supported only by friction, shaking table test to verify its sliding behavior was performed on scaled model. From this shaking table test equivalent friction coefficient that ranges from 0.33 to 0.52 was obtained. This coefficient of friction could be used for seismic response analysis.

During shaking table tests it was observed verified sliding together with in-plant torsional behavior. It is believed that torsional response is due to non-uniform distribution of vertical loads on columns which originates unbalanced frictional forces.

5. References

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