Forced vibration test on wooden model to simulate the seismic behavior of traditional Japanese wooden shrines

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SUMMARY:
Old traditional wooden constructions in Japan are declared as buildings of cultural interest and therefore efforts are done to preserve this kind of building. As a first step for the conservation task, it is important to understand the dynamic behavior of the target buildings. In this study, an attempt to estimate the seismic behavior of traditional wooden shrines is performed by using a test model subjected to forced vibration excitation. The structure corresponds to a framed wooden construction with traditional connections between columns and beams. In general nails are not used in these joints and consist of the beam end narrowed with respect to the rest of the piece and inserted into a hole cut in the column. This joint is known as the mortise and tenon joint. The end of the first member is called the tenon, and the hole in the second member is called the mortise. The joints are wedged to lock it in place. Analytical modeling of this joint becomes a challenge since does not correspond to a rigid joint of a common frame and also it is not a hinge. The stiffness of this joint is between the hinge and the perfect rigid joint. Therefore for analytical modeling semi-rigid joint is used where the moment rotation relationship is specified for each beam end. This research is an attempt to calibrate the analytical model by using experimental results obtained from forced vibration test. Furthermore, the behavior of the supports is investigated taken into account that the bottom part of the columns rest on stone bases and the horizontal action is resisted only by friction.

Keywords: Traditional wooden structure, Rotational stiffness, Forced vibration test, Friction coefficient

1. INTRODUCTION

The traditional wooden structures in Japan, in special those corresponding to temples or shrines, represent architectural heritage which are declared buildings of cultural interest. Therefore, conservation and restoration of these buildings become important tasks. As a first step for these works the understanding of the dynamic or seismic behaviour of this kind of building is a key point. In previous works (Ueda et al 2007 and Cuadra et al 2007) evaluation of dynamic characteristics is done by measurements of ambient vibration which permits to estimate the period of vibration of the structures and sometimes the dumping characteristics are also obtained. The results of the ambient vibration measurements are used to calibrate the analytical model of a specific structure. However the difficulty of modelling appropriately the joints of the traditional wooden structures still represents a source of uncertainty in the analytical results. Then in this study a prototype, which resembles a typical wooden shrine, is constructed to verify its behavior analytically and also experimentally. The test model was subjected to forced vibration excitation and base displacement and acceleration response were measured. Analytical model was elaborated considering semi-rigid joints whit an estimated rotational stiffness. This rotational stiffness was obtained by equations proposed by Yamada et al (2005). Since traditional wooden shrines are not fixed to the foundation, the model of this study was located on a slab surface in such a way that the horizontal resistant force is originated only by friction. The excitation force was harmonic and was applied at selected frequencies to produce the resonance response of the prototype. Measurement of the displacement at the bottom part of the model has permitted to identify the friction coefficient. Therefore the study has permitted to calibrate the analytical model and also to obtained dynamic parameters which will be used for future analysis.

2. CHARACTERISTICS OF PROTOTYPE

The reduced scale model was planned based on the structure of small traditional shrine which is shown in Figure 1. In this Figure a general view of the prototype is also presented. 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 weight of the forced vibration machine.

Figure 1. Typical shrine and prototype

The dimensions of the model are shown in Figure 2 where the values are expressed in mm. Details of the joint are also presented in this Figure and the use of wedges to provide stiffness to the joints can be appreciated. The cross sections of columns are of 60x60 mm and the cross sections of the girders or beams are of 15x60 mm. The top girder is of 60x80 mm to provide more stiffness to the upper part which supports the additional weight of the roof.

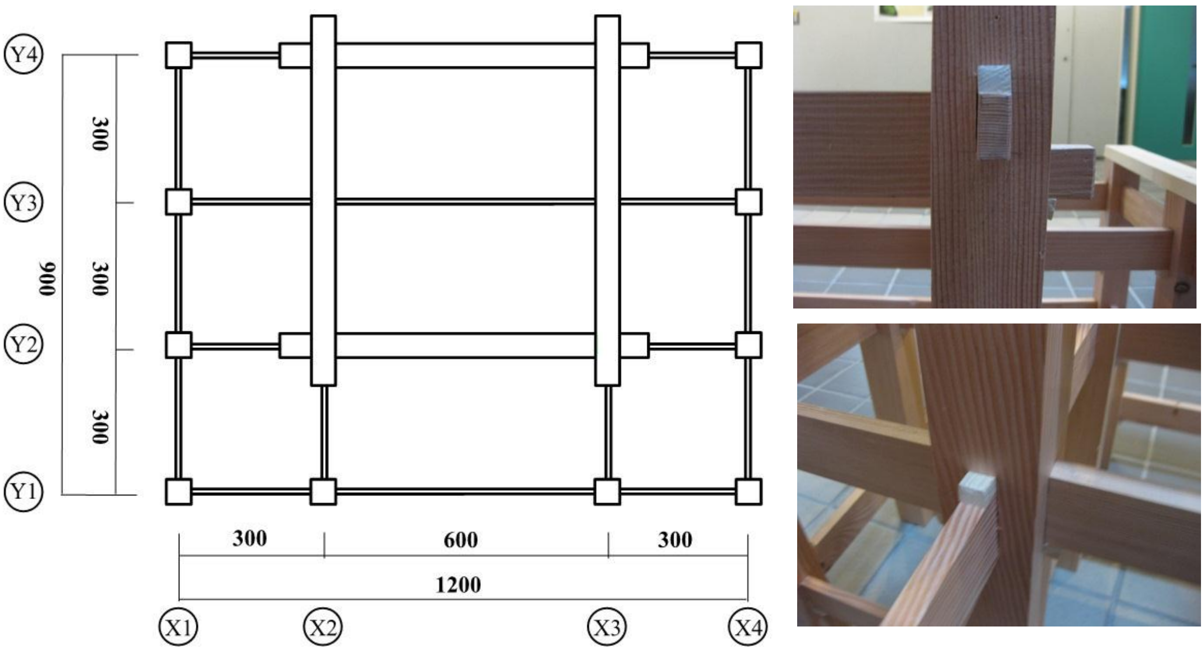

Figure 2. Dimension of the model and joint details

3. DYNAMIC TESTS ON THE PROTOTYPE

Ambient vibration test and forced vibration test were planned to estimate the dynamic characteristics of the prototype. The ambient vibration measurements are used to estimate the predominant frequency of the model and then based on this result the frequency of the forced vibration machine will be setup with the intention of produce resonance of the test model.

3.1. Ambient vibration measurement

Micro vibrations of the model were measured with sensors located at the top panel and one sensor located on ground. Measurements were performed separately for the two principal directions of the model. In all cases the sampling frequency was 100 Hz.

The vibrational characteristics are obtained by calculating the transfer function between the ground level and the top of the model. Figure 3 shows the results for each direction. For the direction parallel to the façade the fundamental frequency of vibration is of 11.33 Hz and the frequency for the ridge direction is 12.79 Hz. It can be observed that for each direction the peak that corresponds to the perpendicular direction also appears in the transfer function. This could signify that torsional vibration is present in the modes of vibration of the test specimen. Then based on the results for the predominant frequencies it is expected that the resonance phenomenon will occur for frequencies around 12 Hz and therefore the forced vibration test must consider this range of frequencies.

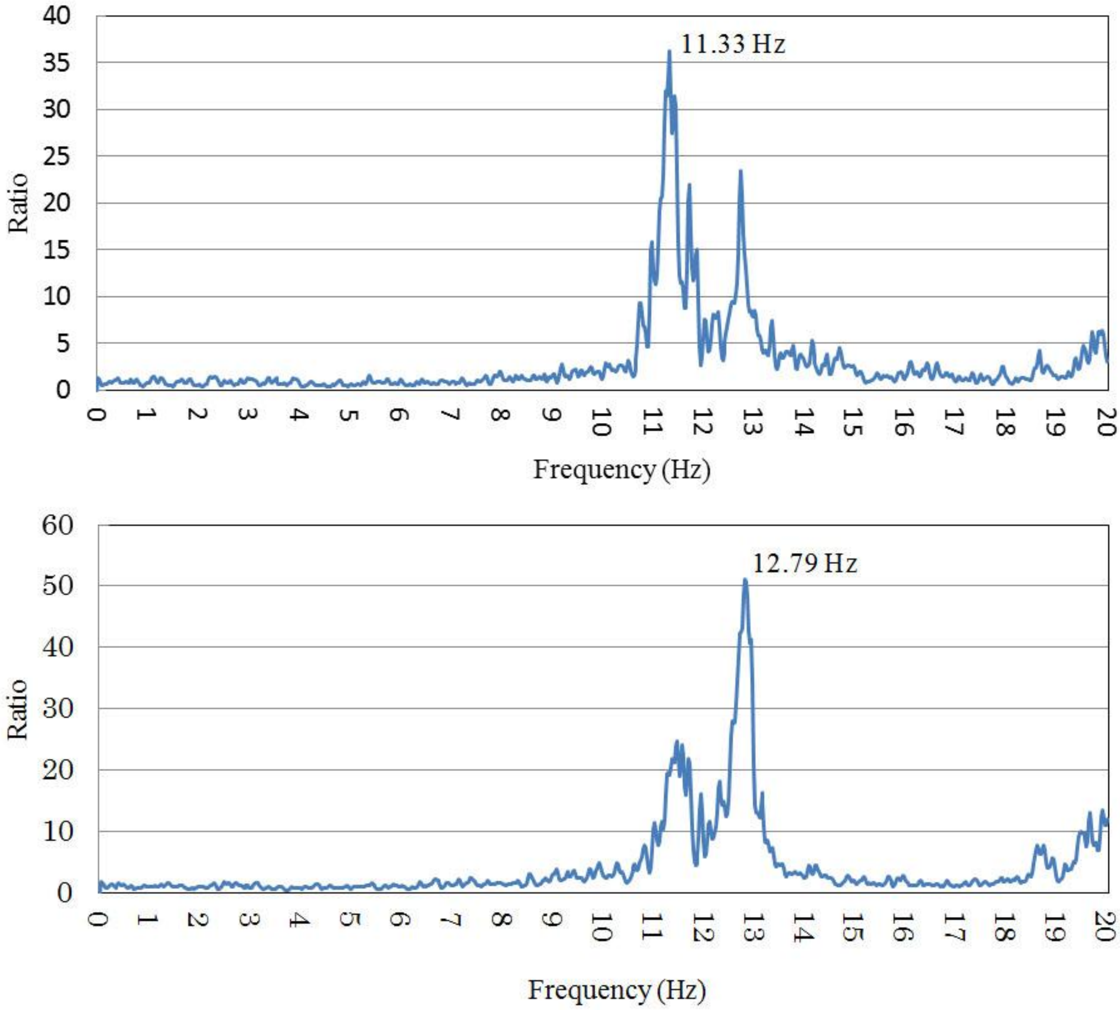

Figure 3. Transfer function of ambient vibration measurements

3.2. Forced vibration test

Forced vibration test was planned to verify the dynamic characteristics of the model and to measure the dynamic friction coefficient between the bottom of columns and the ground surface. The forced vibration machine and accessories result in an additional mass of 24 kg applied on the top of the model. The loading direction is perpendicular to the façade or parallel to the ridge direction. The general layout of the test can be appreciated at Figure 4.

Figure 4. General layout of the forced vibration test

The vibration machine is controlled by a function generator which can applied harmonic waves at specific frequencies. Frequencies of 5 Hz, 10 Hz, 12 Hz, 12.5 Hz and 15 Hz were applied in separately runs. The amplitude for each run was increased by a controller and the applied acceleration was measured by accelerometers located at the top of the specimen. To detect the displacement of the base of the specimen a displacement transducer was located at the ground level. The acceleration of the top mass of the specimen was measured by means of accelerometers located on the wooden plate that replace the roof of the model. In addition new wireless sensors developed by Shimoi et al (2011) is used to verify the sliding of the specimen since these sensors can detect a sudden change in the acceleration which could indicate the sliding of the specimen. All data was collected by the data acquisition system and storage at a computer for their posterior analysis.

Results were obtained in form of time history response of acceleration and base displacement. In Figure 5 the results corresponding to the input wave of 12.5 Hz is shown. Near the resonance frequency it was easier to produce the sliding of the specimen. The detection of the initial sliding of the specimen is important since the acceleration that produces this sliding can be considered to estimate the friction force, and therefore the friction coefficient is obtained as a percentage of the acceleration of gravity. In Figure 5 the estimation of the sliding and the corresponding acceleration is schematically shown. Table 1 shows the estimation of the friction coefficient for 2 cases of forced vibration tests. The average acceleration at time of sliding is divided by the acceleration of gravity to obtain the friction coefficient and it is observed that identical values are obtained for both tests. This coefficient can be used for posterior analysis that considers the sliding behaviour of the base or foundation of this kind of structures.

Table 1. Estimation of the friction coefficient

Forced vibration machine frequency	Acceleration at time of sliding (m/s^2)			Friction Coefficient
	ch1	ch2	average	
12Hz	5.0823	5.2472	5.1648	0.5265
12.5Hz	5.2575	5.0598	5.1587	0.5259

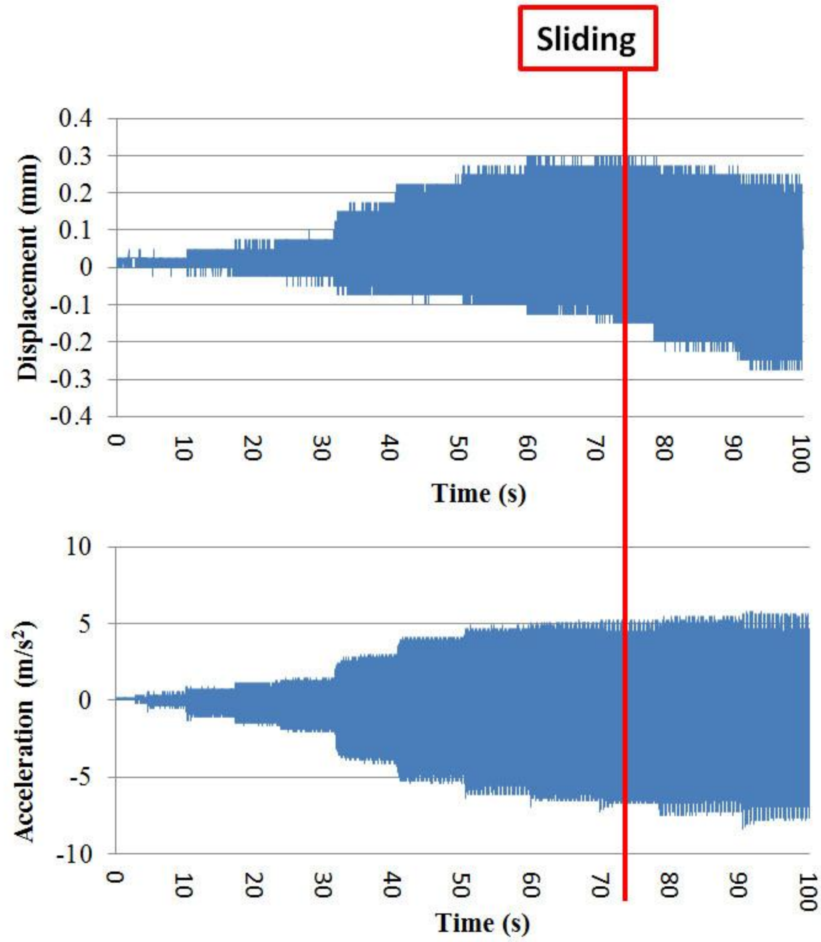

Figure 5. Detection of the sliding and corresponding acceleration for estimation of friction coefficient

4. FINITE ELEMENT MODEL

To construct the FEM model first the characteristics of the joints must be estimated considering that the joints present partial stiffness that is these joints are not ideal rigid joints. Then the joints are modelled with specific rotational stiffness. To estimate this stiffness two kinds of joints are considered as is show in Figure 6.

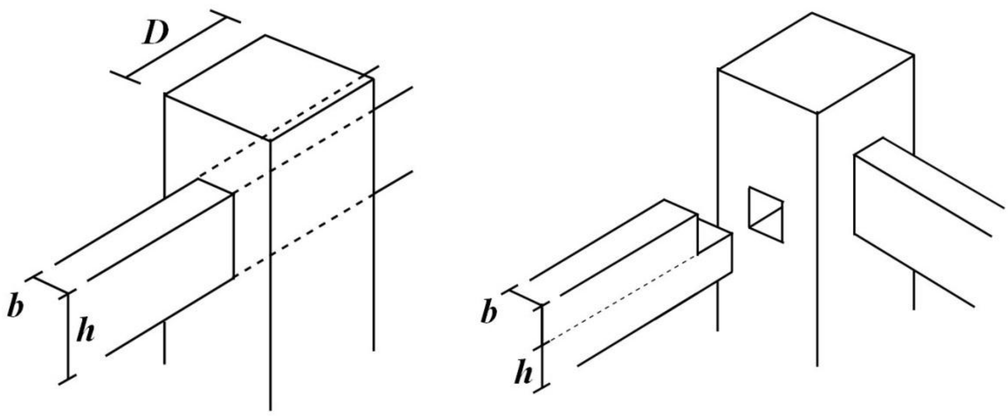

Figure 6. Types of tenon joints for the model

To estimate the rotational stiffness of the joints, equations reported by Yamada et al (2005) are used. These expressions are as follows.

$$K = k_1 + k_2 \tag{1}$$

$$k_1 = \frac{D^3 bE}{4h}\left(\frac{1}{3} + \frac{4h}{3D} + \frac{16h^2}{9D^2}\right), \quad k_2 = \frac{\mu D^2 bE}{4}\left(\frac{1}{2} + \frac{4h}{3D}\right) \tag{2}$$

where

K : rotational stiffness (of the tenon joint)
k_1 : rotational stiffness due to the compressive stress inclines to the grain of tenon
k_2 : rotational stiffness due to the shear force by friction on the tenon
D : column depth b : width of tenon h : tenon depth μ : wood to wood friction coefficient
E : Transversal elastic modulus of beam element

The analytical model is shown in Figure 7, and as can be appreciated the connections of beams to columns are modeled by link elements which permits to specify rotational stiffness for the element ends. In this first step of the research the supports are considered as hinge supports. For posterior analysis frictional properties of these supports will be considered. On the other hand, during the test it was observed that some columns, especially those located in the perimeter, were not in contact with the ground foundation and therefore for another case of analysis the hinge support of these columns are changed to free end.

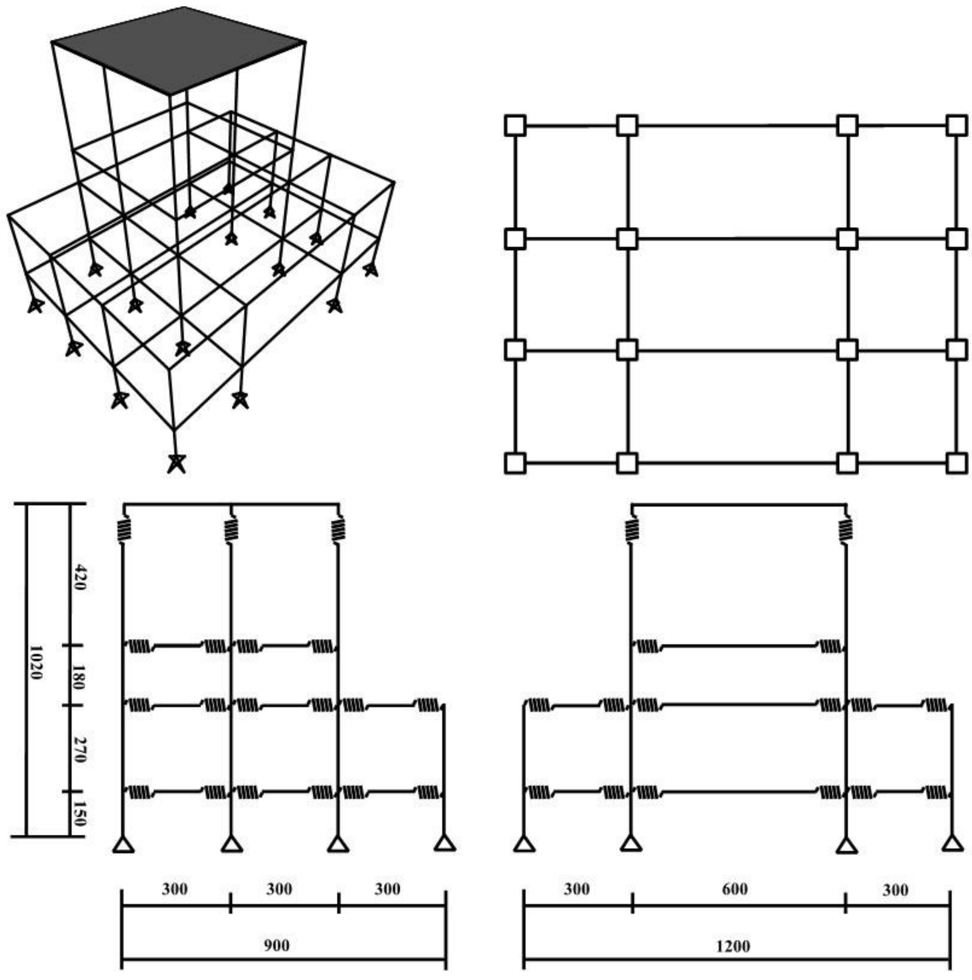

Figure 7. Analytical FEM model

Table 2 shows the comparison between the analytical results and the measured natural frequencies of the scale model when the all supports are considered hinges. Table 3 shows the same comparison when the external hinges are replaced by free ends. In this last case it can be observed that the analytical natural frequencies are closer to the measured ones. As it was mentioned previously not all columns were in contact with the ground and since the central portion supports the additional weight, columns of this portion are surely in contact with the ground. This reduction in the number of effective supports gives as results a lower apparent stiffness and therefore the values of the frequencies decrease.

Table 2. Predominant frequency comparison for hinge supports

Direction	Analysis	Experimental model
Main direction	16.5 Hz	11.33 Hz
Ridge direction	17.6 Hz	12.79 Hz

Table 3. Predominant frequency comparison for partial hinge supports

Direction	Analysis	Experimental model
Main direction	11.9 Hz	11.33 Hz
Ridge direction	15.6 Hz	12.79 Hz

5. CONCLUSIONS

An attempt to estimate the seismic behavior of traditional wooden shrines was performed by using a test model subjected to forced vibration excitation. The structure corresponds to a framed wooden construction with traditional connections between columns and beams which is known as the mortise and tenon joint.

From the forced vibration test was obtained the friction coefficient between the ground support and the bottom parts of the columns. This factor was estimated of the order of 0.5 and could be used for posterior analysis considering the sliding behavior of the supports of this type of structures.

Since the joints are only lock by means of wedges, they are modeled as semi-rigid joint where the moment rotation relationship is specified for each beam end. Although this consideration, the predominant frequencies obtained analytically were higher than those measured experimentally. These differences could be due to that some columns, especially those located in the perimeter, were not in contact with the ground foundation. Therefore the columns of the perimeter were considered as free ends and better approximation to the experimental results was obtained.

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