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SEISMIC PERFORMANCE AND CAPACITY OF KOREAN TRADITIONAL WOOD FRAME BUILDINGS

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SUMMARY

The seismic performance of Korean traditional wood frame buildings with tiled roof was studied through shaking table tests of a full-scale and a half-scale model. These two model structures that represent a part of an existing prototype building structure were constructed through rigorous verification process. The completed models were subjected to two kinds of dynamic test: exploratory and fragility test. The dynamic properties, damage sequence and failure mode of full-scale model matched almost exactly with those of scale model strengthening the reliability of the test results. In particular, fragility test results revealed a new failure mode of the traditional buildings. Important data were obtained from the test that may be used for the calibration of the intensity of historic earthquakes.

INTRODUCTION

Korea is located near the boundary between the Eurasian and Pacific plates. Even though the plate boundary does not directly influence the seismic activity of Korea, nevertheless Korea has a long history of earthquakes. According to an older historic document, the earliest recorded event can be traced as far back as up to 27 AD. There are numerous entries describing strong ground shakings and resulting damages in the Annals of the Choson Dynasty. According to the records, many wooden houses collapsed when the shaking was especially strong and people were killed because of the building damages. In contrast, there cannot be found any record on the collapse of wood frame buildings with tiled roofs. However the Annals recorded that the wood frame buildings rattled very severely, their walls were damaged and tiles fell down to the ground. The shakings made the occupants panic and run outside. Other structures such as parapet of stone city walls and stone beacon lighthouses were recorded as having collapsed due to the strong earthquake ground shakings. Therefore the tests on the seismic performance of traditional wood frame houses would provide data vital for the estimation of shaking intensity of historic earthquakes.

Korean seismologists estimated the magnitude of the largest historic earthquake to be 6.5 or above on Richter scale. Based on their study, the design intensity of 475-year return period design earthquake has been determined to be 0.11g and the maximum credible earthquake 0.22g on firm ground in new

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Korean earthquake design standards [1]. But these estimations were based on the subjective judgments and interpretations of the correlation between shaking intensity and the damage state.
Recently, a series of experimental studies have been initiated in Korea to obtain the data for the correlation between shaking intensity and the damage state. Seo et al. [2] conducted shaking table test of 1/4 scale model of a traditional Korean wood frame building with thatched roof. Kim and Ryu [3] constructed a full-scale model of a 3m tall five-story stone pagoda and investigated its seismic performance using shaking table test. They estimated the intensity of the past earthquake based on the failure mode of the pagoda model.

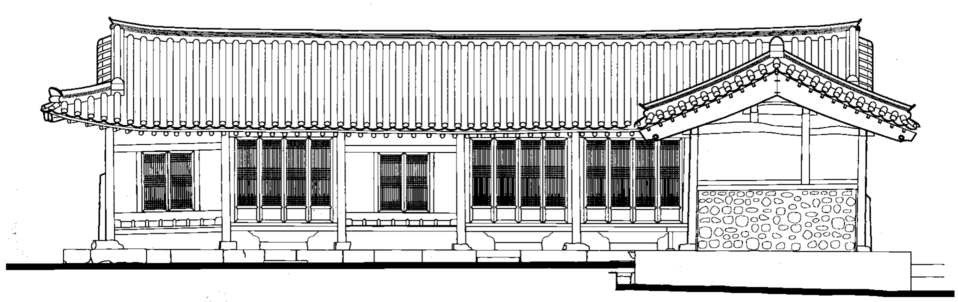
This paper is concerned with the experimental study on the seismic performance of Korea traditional wood frame houses with tiled roof. A full-scale and a half-scale model were constructed through rigorous verification process. The models were tested on the shaking table to obtain data on the correlation between shaking intensity and the damage level. Since the structures show strong nonlinear behavior under strong shaking, it was determined to rely on the full-scale models or large-scale models. It was also determined to reproduce boundary conditions as closely as possible. The column bases of traditional wood structures were just sitting on the pedestal or foundation stone. The present models were constructed and tested under the same boundary conditions. The construction details, test procedures and test results of two large scale models of Korean traditional wood frame buildings are reported. The damage process and failure modes were identified from the test results. The performances of two models were compared with each other. Important data were obtained from the test that can be used for the calibration of the intensity of historic earthquakes.

TEST MODELS

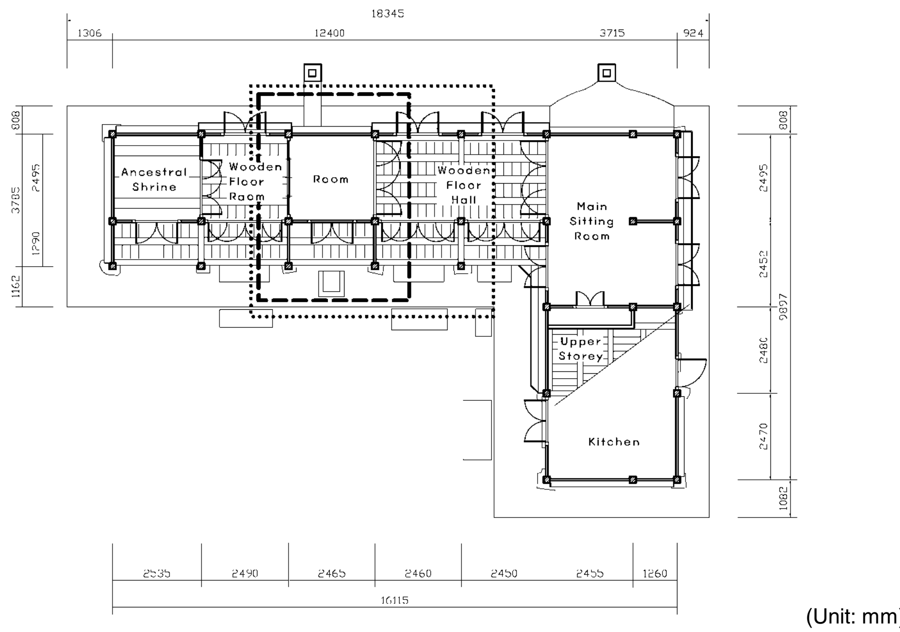
Prototype building

The front and plan view of the prototype building are shown in Figure 1. It was constructed in late 19 C and registered as a Folklore Materials of Gyeonggi-do, Korea. This building has inverted “L” shape plan and considered to belong to a typical wood frame building with tiled roof used as a dwelling house for middle class family in Choson Dynasty.

The prototype house has been well preserved and is still in good condition. The architectural details have been investigated thoroughly. The size and shape of members were measured and recorded extensively. Because this building is a representative one and because it was studied thoroughly, it was selected as the prototype of the models.



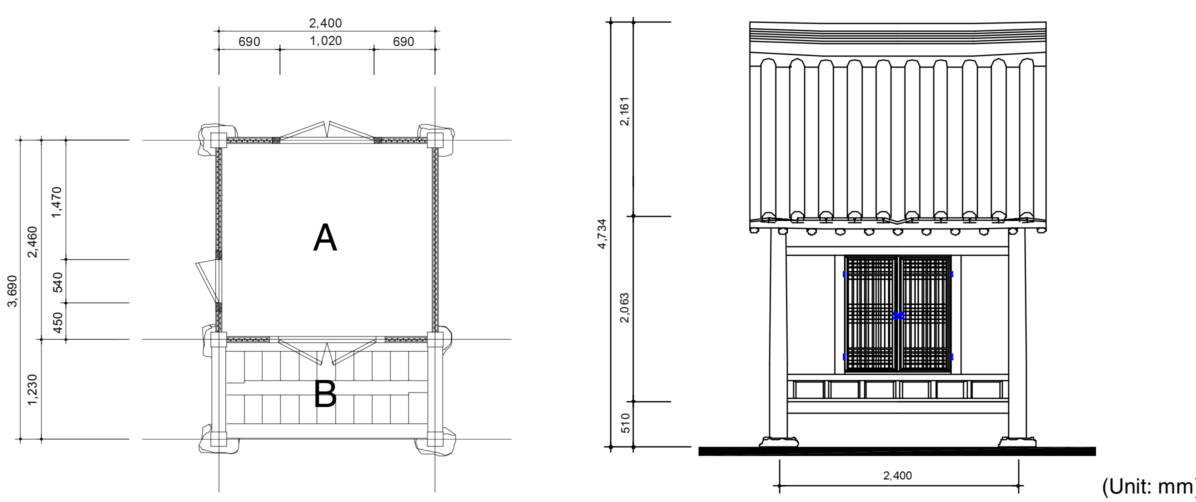
(a) Front view



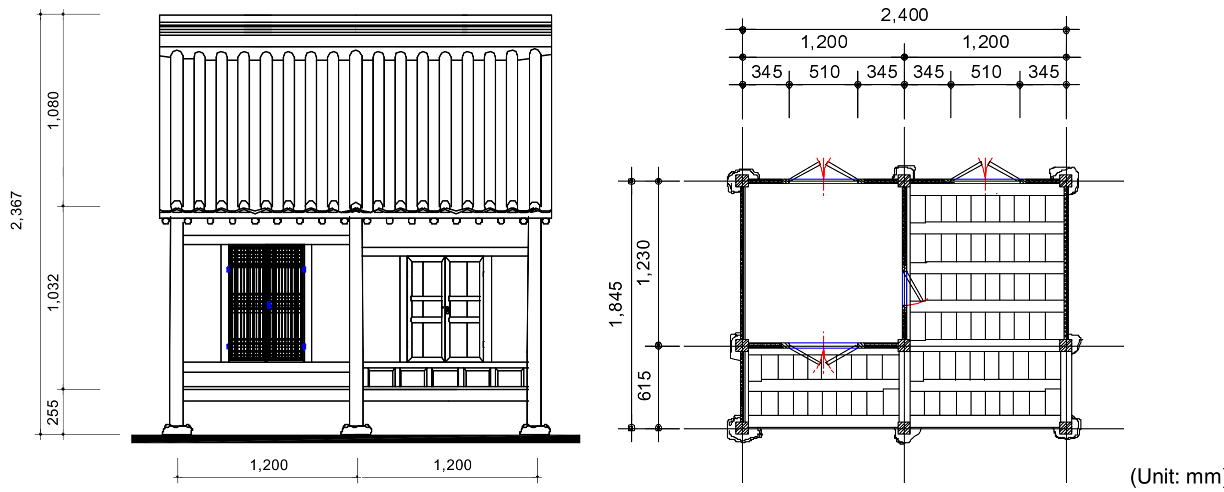
(b) Plan view
Figure 1. Prototype building

Design and construction
Only part of the building was modeled due to the limited capacity of shaking table (payload is 30 tons at 1.5g in horizontal direction). As shown in Figure 1b, the full-scale model represents one bay unit section and the half-scale model corresponds to two bay units section of the building. The front view and plan view of the full-scale and half-scale model are shown in Figure 2 and 3, respectively.

The supplementary weight was added at the roof level so that the columns of the model should carry the same amount of weight as the prototype. But in longitudinal direction the stiffness property of the prototype could not be implemented properly. Therefore test models were supposed to be excited in transverse direction. The same materials as in full-scale model were used for the construction of the half-scale model. Therefore, to satisfy the dynamic similarity rules, it was determined to use the added mass at the roof level.



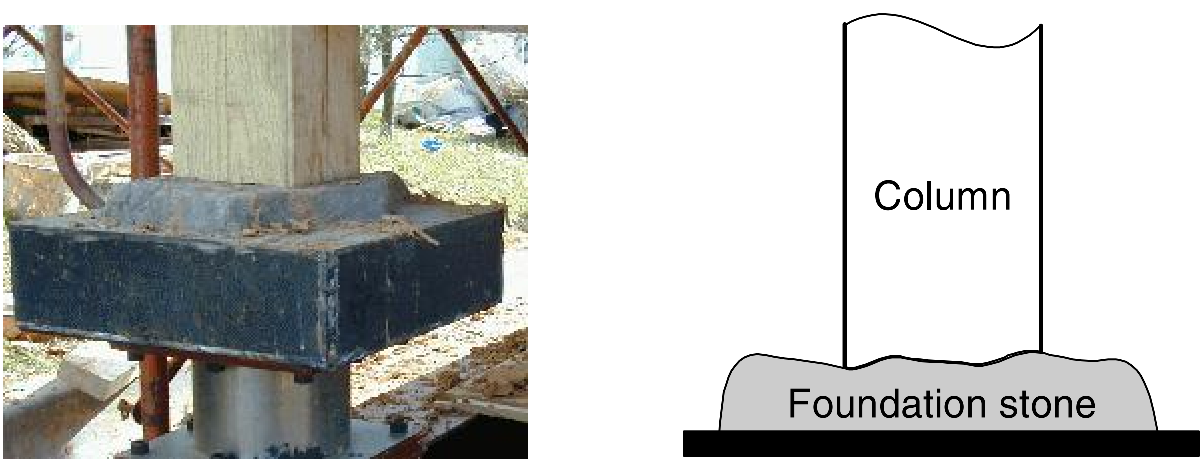
(a) Front view **(b) Plan view**
Figure 2. Design of one-unit full-scale model



(a) Front view **(b) Plan view**

Figure 3. Design of two-unit half-scale model

The old tradition of construction method was followed through the whole procedure. Particularly, as shown in Figure 4a, foundation stones were fixed to bottom steel frame to simulate boundary condition of Korea traditional wood frame buildings as closely as possible. As columns were erected on these foundation stones, the bottom surface of the column was trimmed to fit the foundation surface snuggly so that the column can stand vertically as shown in Figure 4b. There are no sills or grooves that prevent sliding of column base relative to the foundation stone except friction and interlocking coming from the curved interface. Then the beams and girders were connected using tenon-mortise and angle joints. The roof rafters were placed over the beams and columns. The rafters were covered with wood planks on which muddy clay paste was applied evenly. Then the roof tiles were laid on the clay bed. The last step was construction of wall panels. A couple of lintels connect two columns and no diagonal element is used in the frame of wall. The walls were made of clay mixed with straws and added to the lath skeletons. Figures 5 show the completed models mounted on the shaking table.



(a) Column on the foundation stone **(b) Column base sitting on the foundation stone**

Figure 4. Foundation stone and column

(a) Full-scale model **(b) Half-scale model**

Figure 5. Completed models mounted on the shaking table

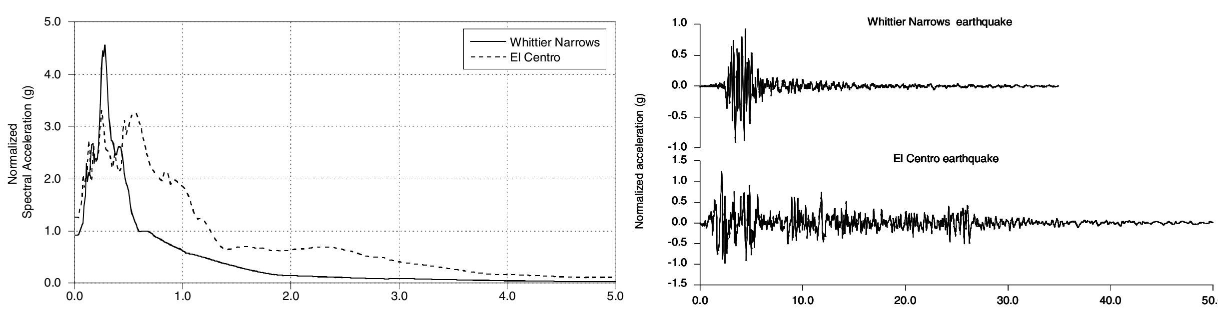
TEST PROCEDURE

Two kinds of test were conducted: exploratory test and fragility test [4]. The objective of exploratory test is to identify the dynamic characteristics of the model such as natural modes, frequencies and damping ratios at low-level excitation. The objective of fragility test is to derive relations between the failure modes of the pagoda model and the intensity and frequency contents of the input earthquake ground motion.

In the exploratory test the model was shaken by unidirectional random table motion in *x*-axis and *y*-axis respectively. In these tests the table was accelerated with the band limited white noise ranging from 0 to 30Hz of the peak acceleration amplitude 0.04g.

As the input motion for the fragility tests, two real earthquake records were chosen: Whittier Narrows earthquake (1987, M 6.1, epicentral distance 8.6km, recorded at USC station 90093) and El Centro earthquake (1940, M 6.9, epicentral distance 8.2km, recorded at USGS station 0117). For horizontal motion the NS components were selected. The intensity of ground shaking is represented by the effective peak ground acceleration (EPGA) of horizontal NS component. It is defined as the average spectral acceleration of 5% response spectrum divided by 2.5. The interval is from 0.1 sec to 0.6 sec for Whittier Narrows and from 0.125 to 0.8 sec for El Centro earthquake. The time histories and the corresponding normalized spectra of NS component of two earthquakes are compared in Figure 6.

The intensity of excitation (EPGA) was increased from 0.04g or 0.08g with 0.04g increments. Up to 0.12g, fragility tests were repeated for both earthquakes. But beyond 0.12g, the fragility tests were conducted with the simultaneous excitation of NS and UD components of El Centro earthquake only.



(a) Normalized time histories **(b) Normalized response spectra (5% damping)**

Figure 6. Input earthquake acceleration records

TEST RESULTS

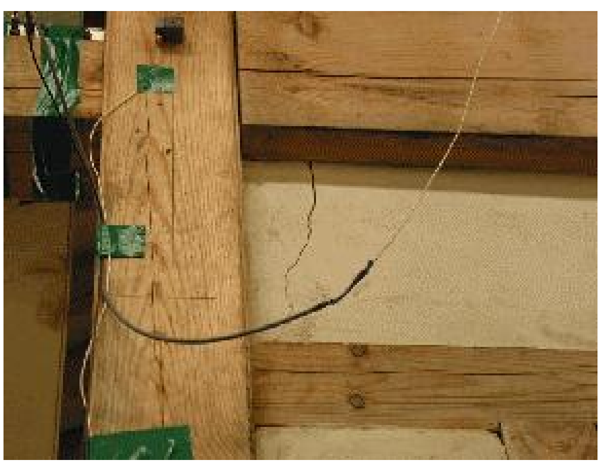
Exploratory test

The natural periods and mode shapes of the fundamental mode in transverse direction were identified from the exploratory test results. Both models vibrated like a single degree of freedom system with a lumped mass at the roof level. The coupled torsional motion was negligible. The natural periods of the first mode were 0.64 sec and 0.58 sec for full-scale and half-scale model, respectively. The corresponding damping ratios were 16.75 % and 13.24%. Even at the very low level of excitation the damping ratios were remarkably high. It may be attributed to the dissipation of energy due to the friction at the beam-column joints. The wall panels might have contributed to the energy dissipation through friction with frames. The natural periods are longer than the results by Seo et al. [2]. It may be partly due to the fact the weight of roof of the present model was much heavier than the model by Seo et al. [2]. However, the natural period of traditional wood frame buildings was considerably longer than other type of structures with the comparable height.

Fragility test

The damage states of the full-scale model at various excitation levels are shown in sequence in Figure 7. Only moderate level of damage was observed at the intensity of EPGA less than 0.2g. Figure 7a shows that cracks began to appear on wall panels at EPGA 0.12g. The real damage was initiated by the sliding of column bases on the foundation stone. The tenons of lower beams began to be pushed out of the mortises in the columns leading to the separation of wall panels. As the intensity increases the lower frame beams separated from the columns first (Figure 7b). Then the beams at the mid height separated from the column (Figure 7c). If the intensity became even higher, the wall panels fell down to the ground along with the beams (Figure 7d). In the course of tests, loud sounds were heard that might be due to fracture of members at the joints. However, the test model maintained its structural integrity or load carrying capacity even at the excitation level as high as 0.36g. The test stopped at this intensity level to avoid damage to the equipment due to the complete collapse of the model. The total collapse of the model might have occurred at the intensity level 0.4g or higher.

The damage sequence and failure mode of the half-scale model was similar to the counterparts of the full-scale model. The complete damage of half-scale model (Figure 8) occurred at the intensity of EPGA 0.36g was almost identical with that of the full-scale model (Figure 7d). However, it has to be pointed out that the roof tiles did not fell down to the ground at all contrary to the initial expectation.



(a) Crack on a wall panel at 0.12g

(b) Separation of wall panel from frame at 0.24g

(c) Separation of wall panels from frame at 0.28g **(d) Falling down of wall panels at 0.36g**

Figure 7. Damage sequence of full-scale model

Figure 8. Collapse of wall panel of half-scale model at 0.36g

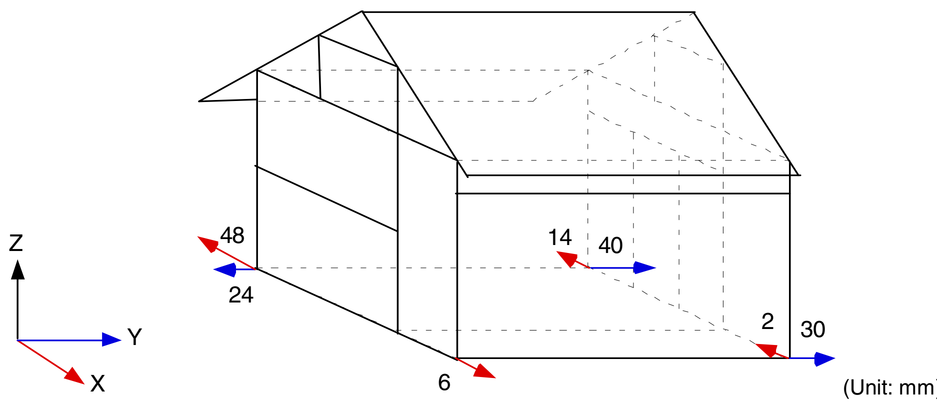
FURTHER EXAMINATION OF TEST RESULTS

The behavior of the model was observed to be sensitive to the characteristics of input motion. The difference of response between unidirectional (XX) and bi-directional (XZ) excitations appears to be very minor for the low level excitation. On the contrary, the responses due to El Centro earthquake were significantly higher than those due to Whittier Narrows earthquake. It can be explained in part by the shape of response spectra. The ordinate of El Centro response spectrum is much higher in the long period range than Whittier Narrows spectrum as can be seen in Figure 6b. As the intensity increases the natural period will become longer indicating that the difference will be become even larger. It implies that these wood frame buildings might withstand higher intensity ground motion of short period characteristics than that of long period ones. Seo et al. [2] reported similar observations in their study on the wood house model with thatched roof.

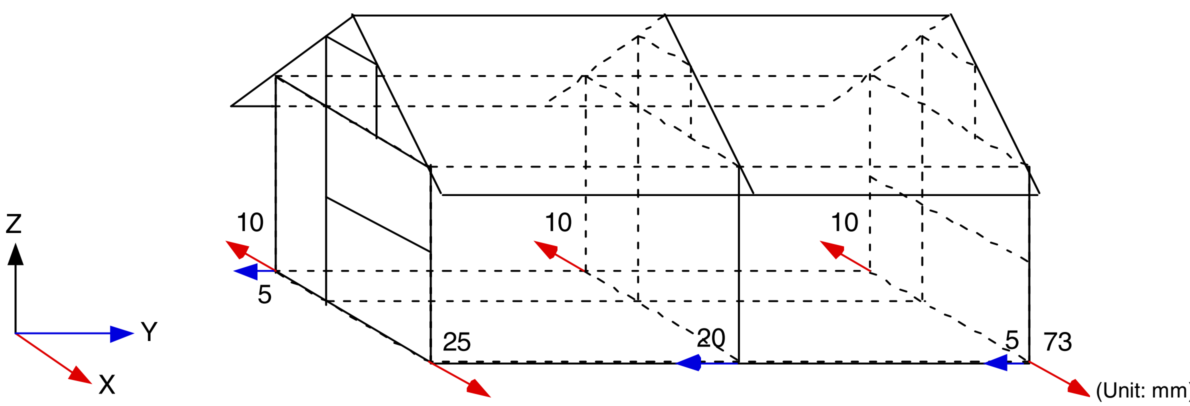
The horizontal movement of column bases on the foundation stone and resulting prying action appears to have initiated the damage to the wood frame building. Figure 9a and 9b show the close-up pictures of a column base of the full-scale model at EPGA 0.24g and 0.28g, respectively. The trace of sliding can be clearly visible. The movement of column base occurred in both horizontal directions at EPGA 0.36g as shown in Figure 10. Suzuki et al. [5] observed similar mechanism in the shaking table test of Japanese traditional wood house model.

(a) At 0.24g (b) At 0.28g

Figure 9. Close-up view of the movement of column base



(a) Full-scale model



(b) Half-scale model

Figure 10. Movement of column base on the foundation stone at EPGA 0.36g

The seismic capacity of the present models seems to be much stronger than that of the models studied by Seo et al. [2]. Even though they had thatched roof, their capacity was expected to be similar to the building models with tiled roof of the present study. There were similarities between their model and present ones. But the present models are different in three aspects. First, the scale of present models is much larger than the models of Seo et al. [2]. Second, the present models had wall panels. Third and most importantly, there was difference in boundary condition of test models. The present models were constructed and tested under the same boundary condition as traditional wood structures. On the other hand, Seo et al. [2] made the column base as hinge support. Therefore the sliding and rocking of the model were not allowed.

The test result of present models shows clearly that the failure was initiated from the sliding and rocking of column base. Even though the rocking and sliding of column bases lead to the progressive damage of the model, but the rocking and sliding might have contributed considerably to the increase of seismic capacity of the models. Housner [6] discovered that elevated tanks performed very well just because it was allowed to rock. Due to the rocking and sliding, the effective period of the model might have shifted to lower range and increased the damping capacity. And the base shear was limited delaying the failure of roof joints. In addition, the cracks of wall panels and friction between wall panels with frames might have contributed to the increase of energy dissipation capacity of the model.

CONCLUSIONS

Two models were constructed to study the seismic performance of Korea traditional wood building with tiled roof. These models, a full-scale and a half-scale model, represent part of an existing prototype building. The completed models were mounted on a shaking table and the dynamic characteristics and seismic capacity were investigated through exploratory test and fragility test. Even though there was difference in scale factor, there were very strong similarities in dynamic properties, damage sequences and failure mode between two models.

It was found that the movement of column base on the foundation initiated damage to the structure. This movement was caused due to sliding and rocking of columns and structure as a whole. The movement of column base leads to disintegration of lower frame and wall panels but still the load carrying capacity sustained because the joints of roof frame maintained the integrity of the structure. The sliding and rocking of column base contributed to good seismic performance of the models. The dissipation of energy by joints and non-structural components may contribute to this good performance.

These tests were conducted under the various limitations. Nevertheless, the damage sequence of Korea traditional wood frame buildings with tiled roof due to earthquake ground motion was understood clearly. Important data and information were obtained from the test that can be used for the calibration of the intensity of historic earthquakes.

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