13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1487

SEISMIC PERFORMANCE OF WOOD HOUSES BY FULL-SCALE SHAKING TESTS OF TWO-STORIED POST AND BEAM WOODEN FRAMES

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SUMMARY

Destructive shaking table tests were carried out to evaluate seismic performances of wooden frames with various seismic resistance elements. The basic test specimen was a full-scale two-story post-and-beam wooden frame. Three structural elements: wooden braces, plastered mud-walls, and plywood-walls were added to the basic model respectively to constitute three test specimens. Different modes for wooden house damages and failures were observed. Quantitative relationships between restoring forces and deformation angles for the specimens were established and compared. Relative merits of the three seismic resistant elements are analyzed. An analytical method to evaluate seismic performances of wooden houses is applied to the test specimens, and obtained results are compared with the test results.

1. INTRODUCTION

Severe damages even collapses took place for many wooden houses during earthquakes in Japan. In the 1995 Hyogoken-Nambu earthquake alone, more than a hundred thousand wooden houses collapsed, and much more suffered from damages to different extents. Since earthquakes of medium to strong intensities occur quite frequently and most of residence houses in Japan are wooden houses, it is in urgent desire to take appropriate structural measures to enhance seismic resistances of existing wooden houses and to develop seismic design codes for new wooden houses. It is known that the seismic performance of a wooden house will be substantially improved if certain structural elements are built in. Among them, braces and walls are most widely used to enhance earthquake-resistance capacities of wooden houses. In the present investigation, destructive shaking table tests were carried out on full-scale models of two-story wooden frames with three seismic resistant elements: wooden braces, plastered mud-walls, and plywood-walls, respectively. Different types of damages and failure modes were observed for different specimens, and relationship of restoring forces and deformation angles were established. Comparisons are made for the three structural elements, and their relative advantages are analyzed. Finally, an analytical method is

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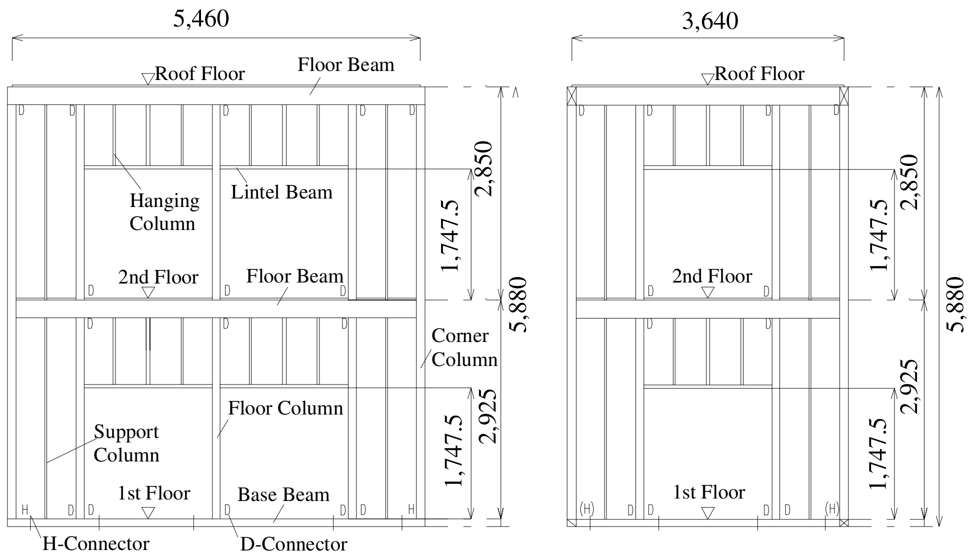


a) In width direction b) In depth direction

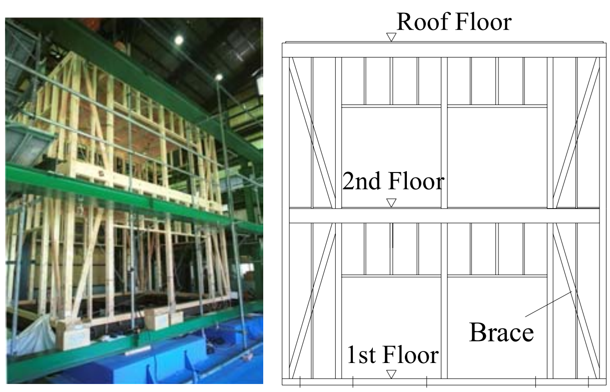
Fig.1 Elevations of full-scale specimens. (in mm)

applied to the test specimens to evaluate their seismic performances, and the obtained results are compared with the test results.

2. FULL-SCALE SPECIMENS

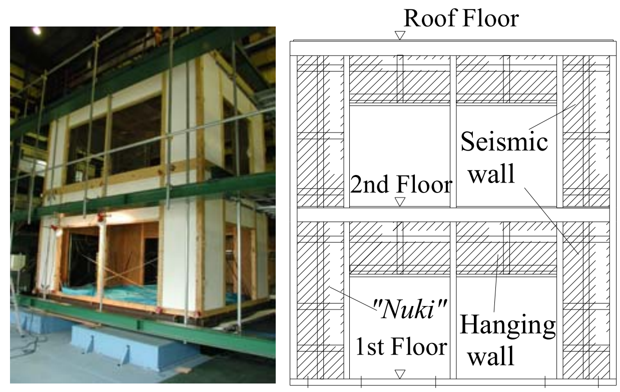
The basic full-scale specimen, called *frame specimen*, is a two-story post-and-beam wooden frame structure, as shown schematically in Figs. 1(a) and 1(b). Its height is 5880mm, width 5460mm, and depth 3640mm. Four *base beams* were connected in a rectangular shape, and fastened horizontally to the shaking table by screws. Four major columns, called *corner columns*, were set at the four corners from the base beams to the roof of the specimen. Four beams, called *floor beams or ceiling beams*, were used to connect the four corner columns at the second floor level, as well as at the roof level. In each story, ten *floor columns* were installed between the floor and the ceiling, eight *supporting columns* of smaller size and same length were installed between the floor columns and corner columns, and six short beams called *lintels* were used to connect two neighboring columns at a height of 1747.5mm above the floor. Three short columns, called *hanging columns*, connected a lintel to a ceiling beam. Cross-sections of all columns and beams were rectangular or square, and their sizes are listed in Table 1. Two types of metal connectors were used at the column-bean joints. A H-connector was hole-down type used to resist an axial load, while a D-connector was right-angle type with one side being a triangle (Delta) shape used to resist a rotational moment. Metal screws were used in the connectors. Locations of the two types of connectors are also shown in Figs. 1(a) and 1(b) by H and D letters. All columns and beams were made of glulam so that their Young‘s modulus was the same and known accurately. Plywood with a thickness of 24mm was laid on both the second floor and the roof in order to raise the stiffness of the specimen in horizontal directions.

The second specimen, called *frame with wooden braces*, was built from the frame specimen by adding wooden braces, as shown in Figs. 2(a) and 2(b). The cross-section and material of the braces are listed in Table 1. Braces were installed between neighboring corner columns and floor columns in diagonal directions. Plate metal connectors were used to fasten the two ends of wooden braces to columns and beams. Nails were used to fasten braces to supporting columns in the middle.



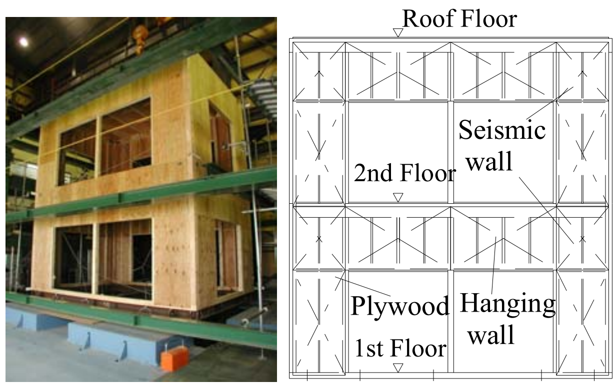
a) Picture b) Elevation

Fig.2 Specimen with wooden braces.



a) Picture b) Elevation

Fig.3 Specimen with mud-walls.



a) Picture b) Elevation

Fig.4 Specimen with plywood-walls.

Table 2 List of weight for three specimens. (in kN)

	1st Floor		2nd Floor	
	Dead load	Weight	Dead load	Weight
Frame	9.93	27.95	9.06	29.42
Frame with braces	10.57	27.95	8.97	29.42
Frame with mud-walls	29.81	25.40	22.48	29.42
Frame with plywood-walls	13.88	27.95	10.49	29.42

Table 1 Detail of wooden members. (in mm)

Member	Floor Beam	Base Beam	Lintel Beam	Corner Column	Floor Column	Support Column	Hanging Column	Brace	*"Nuki"*
Size	105×240	105×105	27×105	120×120	105×105	27×105	27×105	45×105	15×105
Kind	Glulam							Douglas fir	Cryptomeria

The third specimen was *Frame with mud-walls*, also constructed based on the frame specimen by installing mud walls, as shown in Figs. 3(a) and 3(b). It should be pointed out that all supporting columns and hanging columns were removed for the convenience of building mud-walls. The thickness of mud-walls was 60mm. Two types of mud-walls were distinguished according to their seismic roles. One is called seismic walls between neighboring corner columns and floor columns. Mud-wall was constructed in a common way used in Kyoto, Japan. Inside the walls, ribs were added to reinforce the walls, called "*nuki*" in Japanese. In each seismic wall, one vertical "*nuki*" and three horizontal "*nuki*" were added, while in each hanging wall, two horizontal and one vertical. The size and material of "*nuki*" are also listed in Table 1. Finish coating was applied after undercoating, and a 2mm-thick layer of white plaster covered the outside of the mud-walls.

In the specimen called *frame with plywood-walls*, as shown in Figs. 4(a) and 4(b), plywood panels of 12mm thickness ware placed onto columns and beams of the frame specimen. N50 steel nails were used to fasten the panels with a uniform space of 150mm. The difference of seismic walls and hanging walls is the same as the case of mud-walls.

To be more comparable to real wooden houses, iron plates were placed on the second floors and the roofs of all specimens. An iron plate of 29.42kN was placed on the roof of each specimen. For the second floor, an iron plate of 25.40kN was used for the specimen with mud-walls and one of 27.95kN for the

Dead loads, which are required in calculations, were measured before assembling. The added weights of the iron plates and the dead loads are listed in Table 2.

3. SHAKING TABLE TESTS AND RESULTS

Outline of destructive shaking table tests

Destructive shaking table tests were carried out in Disaster Prevention Research Institute at Kyoto University. Various censors and instruments were used to measure displacements, accelerations and strains at appropriate locations. The shaking direction was only in the longer-span (width) direction for all specimens in the present investigation. The recorded NS component of the ground acceleration of 1940 El Centro earthquake was used as input to the shaking table. To evaluate seismic performances of the specimens at different excitation intensities and reach destructive states, the wave was scaled with the maximum acceleration from 50Gal up to 1000Gal using 50Gal as an increment. This maximum acceleration for the scaled 1940El Centro NS will be used to specify the excitation level hereafter in the text and figures.

Descriptions of tests results

Frame specimen

Three levels of excitations were applied: 50Gal, 100Gal, and 150Gal, and measured deformation angles were less than 1/60rad. No damages occur during the tests. Since the frame specimen was to be used to construct the frame with mud-walls, destruction tests were not performed.

Frame with wooden braces

Creaking sounds were heard at the two end joints of four braces in the first story starting from the deformation angle of 1/220rad (100Gal). As the deformation angle increased to 1/87rad (150Gal), cracks occurred at the joints of the braces and the supporting columns. When the angle reached 1/32rad (350Gal), one brace was broken, as shown in Fig. 5. Then three braces in the front and back were broken sequentially at the angles of 1/27rad (400Gal), 1/23rad (600Gal), and 1/15rad (800Gal). At the same time as the four brace was broken at 1/15rad (800Gal), cracks were observed in a corner column at the ceiling height of the first story. Cracks in another corner column at the same height appeared when the angle reached 1/9rad (1000Gal). And immediately the other two corner columns were cracked. The situation of destruction is shown in Fig. 6. All damages took place in the first story.

From the above destruction process, it was found that the break of the first brace at an angle of 1/30rad was a critical point for the frame. After this point, other braces, as well as corner columns, were cracked quite fast. Similar observation was also found in previous research [1] from static and dynamic tests. Therefore, it could be concluded that wooden brace may lose seismic resistant capacity at the specimen deformation angle of about 1/30rad.

Frame with mud-walls specimen

At the deformation angle of 1/230rad (100Gal), the first crack in a seismic wall started from a corner column at a height of 1600mm of the first story. The crack was in an inclined direction. When the deformation angle reached 1/155rad (150Gal), the first crack propagated further, more cracks appeared in the seismic walls of the second story and near H-connectors at three corners on the first floor. As the angle increased to 1/64rad (250Gal) and 1/51rad (300Gal), more cracks occurred in mud-walls in the first story and old cracks propagated longer and wider. When the angle reached 1/31rad (500Gal), hanging walls began to separate from floor columns, and one lintel in the first story started to fall out from floor columns. As the angle was increasing, cracks became visible on the inside of the walls, and four corners of each seismic wall and each hanging wall began floating away from the frame. The tests ended when many mud-walls of the specimen were damaged severely at the angle of 1/16 (800Gal). Fig. 7 is a picture of such destruction state.

Fig.5 Break of wooden brace in first story.

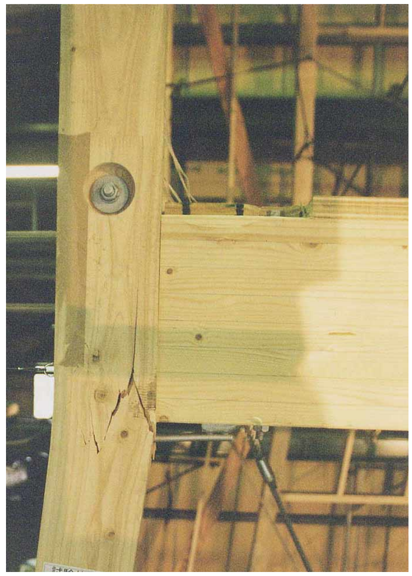


Fig.6 Break of corners column at first story's ceiling.

Fig.7 Separation of mud-walls from frame.

Fig.8 Fracture of nails used for plywood-walls.

Fig.9 Separation of plywood-walls in first story.

After the tests, it was found that all structural members, such as columns and beams, were not damaged. Thus, the mud-walls contributed quite high resistance to the specimen. During the test process, the initiation of small cracks in the walls and the propagation of the cracks to larger sizes released stresses, dissipated energy, and prevented the frame from destruction.

Frame with plywood walls specimen

Creaking sounds began to be heard at the deformation angle of 1/410rad (150Gal), and became clear at the angle of 1/290rad (200 Gal). When the angle reached 1/165rad (250Gal), it could be identified from the sounds that plywood panels collided with each other in the first story. As it reached 1/68rad (350Gal), nails at four corners of seismic walls in the first story started to bend, edges of two neighboring plywood panels began to fall apart from each other, and then the nails were pulled out from plywood surface. When the angle increased to 1/28rad (600Gal), fracture of nails along the perimeter of seismic walls took place, as shown in picture 8. The outside of seismic walls separated from the frame, and only middle areas were connected to the supporting columns by nails, as shown in picture 9. At the angle of 1/11rad (800Gal), cracks occurred in the lintels of the first story. Finally, the test stopped at the angle of 1/10rad (1000Gal), when the H-connectors at four corners on the first floor began to bend.

The destructive tests on the frame with plywood-walls showed that the plywood-walls lost the seismic resistance due to the bending and fracture of the connecting nails. However, the plywood-walls did provided considerable strength to the frame, and allowed largest deformations of the frame.

Hysterics characteristics

To investigate dynamic behaviors of the three seismic resistant elements quantitatively, hysterics characteristics of restoring force-deformation angle relationship were evaluated. Only the first story was considered since most damages took place in the first story for all specimens. The restoring forces were calculated from specimen masses and measured accelerations, while the deformation angles were calculated from specimen heights and measured displacements. Hysteresis loops are depicted in Figs. 10 through 13 for the four specimens, respectively, at several different excitation levels. Skeleton curves are shown in Fig. 14 for the entire testing processes.

As mentioned previously, the frame specimen was tested up to 150Gal excitation level. The maximum deformation angle was 1/67rad, and the maximum restoring force was 6.2kN. It is seen that the stiffness almost kept unchanged, and the areas of hysteresis loops were small, indicating a low energy-dissipation ability. It should be pointed out that metal connectors were used for all joints in the fame; thus, making the frame quite rigid.

For the frame with wooden braces, the onset of the brace break was at the deformation angle of 1/30rad (350Gal). Near this point, the frame reached its maximum restoring force of 30.4kN. After the first brace was broken, the restoring force no longer increased, but the deformation increased rather rapidly. When all braces in the front and back of the first story were broken at the angle of 1/15rad (800Gal), frame damages followed immediately.

The frame with mud-walls had a slightly lower stiffness than that of the frame with wooden braces up to an angle of 1/120rad, indicating the braces and mud-walls provided almost the same additional stiffness to the frame. The maximum restoring force reached 45.5kN (700Gal) at an angle of 1/19rad when the mud walls separated from the frame and no longer supplied additional strength to the frame. As mentioned before, no fame damages were founded at the angle of 1/16rad (800Gal).

The frame with plywood walls showed the highest stiffness among the four specimens. It reached the maximum restoring force of 79.2kN (500Gal) at an deformation angle of 1/36rad when the nails connecting the plywood panels to the frame began to fracture and the plywood walls started to lose their ability to provide additional strength. After this point, the restoring force decreased rapidly. At an angle of 1/11rad (800Gal), the frame damages occurred.

Comparing the three specimens with wooden braces, mud-walls and plywood-walls respectively, it could be concluded that the frame with mud-walls had the best seismic performance. It did not have frame damages up to the deformation angle of 1/16rad (800Gal), while in other two cases, frame damages occurred at this level of excitation. It was more pliable than the frame with plywood-walls, and has larger capacity to dissipate energy as indicated by the larger areas of the hysteresis loops in Fig.12. It is noted that the stiffness and the maximum restoring force are not the most important parameters of the seismic performance.

Natural frequencies and damping factors

Before the destructive tests, the specimens were tested for their natural frequencies and equivalent damping factors. A sweeping sinusoidal wave was used as input to the shaking table to determine natural frequencies of the specimens. The frequency of the sweeping sinusoidal wave ranged from 0.3Hz to 20Hz with an increment of 0.1Hz. It is known that the natural frequency of a system with a nonlinear restoring force is not a constant, and it varies with the deformation amplitude. Thus, the amplitude of the sinusoidal wave was also set at different levels so that natural frequencies for different deformation angles could be obtained. To determine the natural frequencies, measured accelerations were used to calculate acceleration transfer functions.

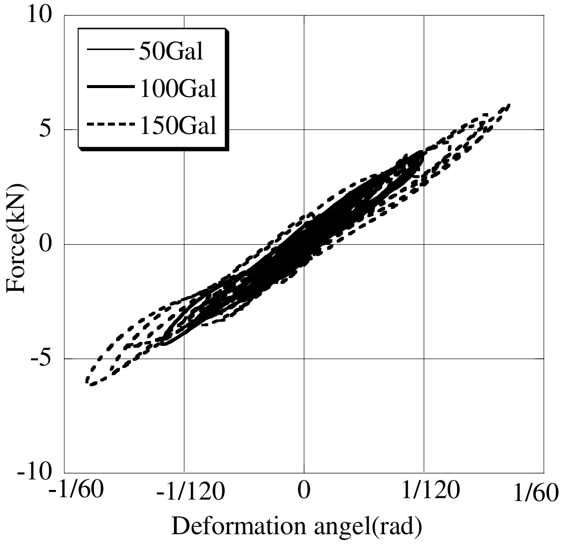


Fig.10 Hysteresis loops for frame specimen.

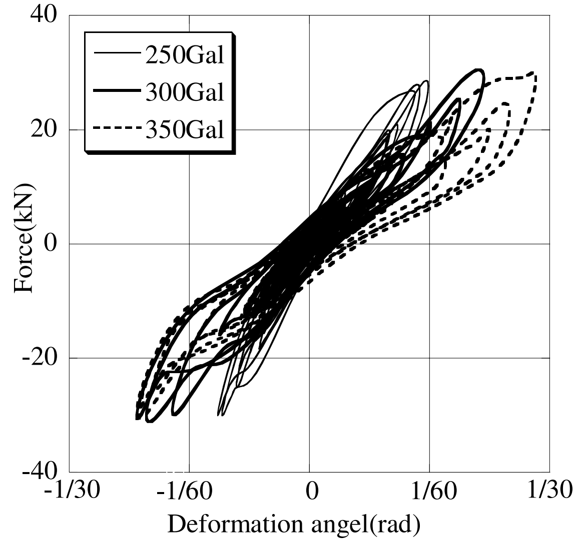


Fig.11 Hysteresis loops frame with wooden braces.

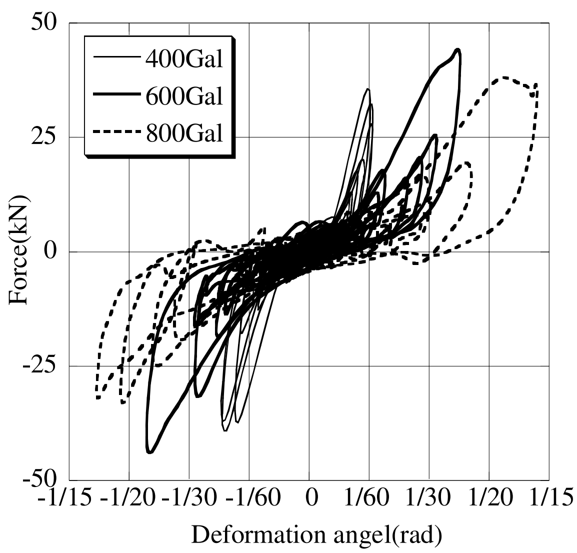


Fig.12 Hysteresis loops frame with mud-walls.

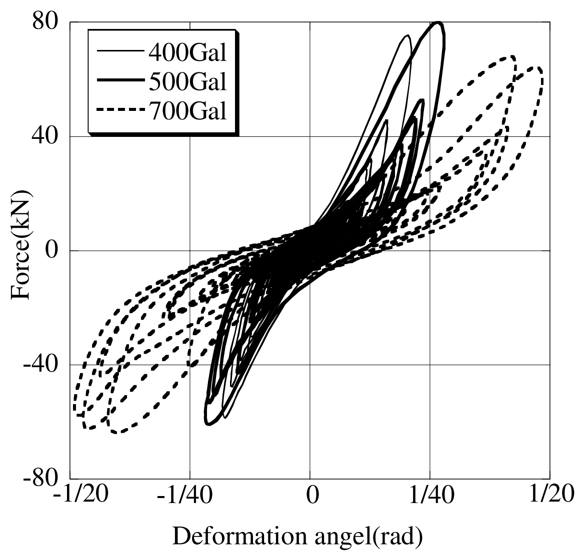


Fig.13 Hysteresis loops frame with plywood-walls.

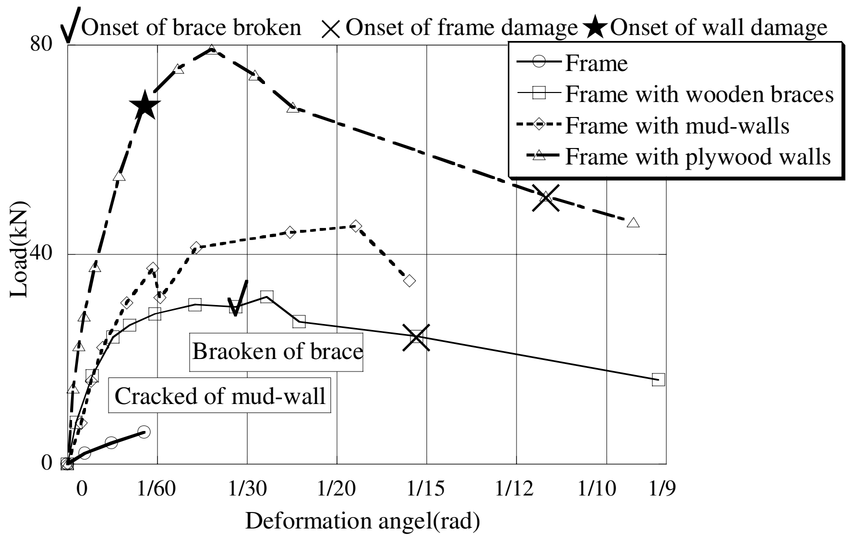


Fig.14 skeleton curves for four specimens.

The major peak location of each transfer function was the fundamental frequency of the corresponding specimen at the corresponding deformation angle. We called this fundamental frequency as the natural frequency of the specimen.

After the natural frequencies of the specimens were determined, a sinusoidal wave with a specific natural frequency was used as input to the shaking table, and a stable hysteresis loop was obtained. From the loop, the area A, the maximum deformation δ, and the maximum force P were obtained. It is known that the area of a hysteresis loop represents the dissipated energy in one cycle, and the energy dissipated by an equivalent linear viscous damping in one cycle is $2\pi\zeta P\delta$ where ζ is the viscous damping factor. By equating these two dissipated energies, i.e. $A = 2\pi\zeta P\delta$, the equivalent damping factor can be found as $\zeta = A/2\pi P\delta$.

The natural frequencies and the equivalent damping factors were also calculated for higher deformations during the destructive tests. For each excitation level, the largest hysteresis loop was used in calculation following the same way as in the case of a sinusoidal excitation.

The evaluated natural frequencies and equivalent damping factors are shown in Figs. 15 and 16 respectively, where the hollow symbols are the measured values using sinusoidal waves, while the solid symbols are those measured during the destructive tests. As expected, the frame specimen had the lowest natural frequencies. Among the three frames with additional resistant elements, the frame with plywood-walls had the highest natural frequencies, while the frame with mud-walls had the lowest ones. When the deformation angle was below 1/1000rad, the frame with wooden braces and the frame specimen had almost the same equivalent damping factor less than 5%. As the angle increased, the equivalent damping factor of the frame with wooden braces increased to about 10%, higher that that of the frame specimen of about 7%. The Equivalent damping factors for both the frames with mud-walls and with plywood-walls were between 10% and 14% in almost entire range of the deformation angle.

4. ANALYTICAL EVALUATION METHOD OF SEISMIC PERFORMANCE

Since the Building Standard Law of Japan was revised in June 2000, the response limit strength design method has been applied for structure design. In the method, a multi-story building is replaced by an equivalent SDOF system. Then the deformation angle of the SDOF system to the design acceleration

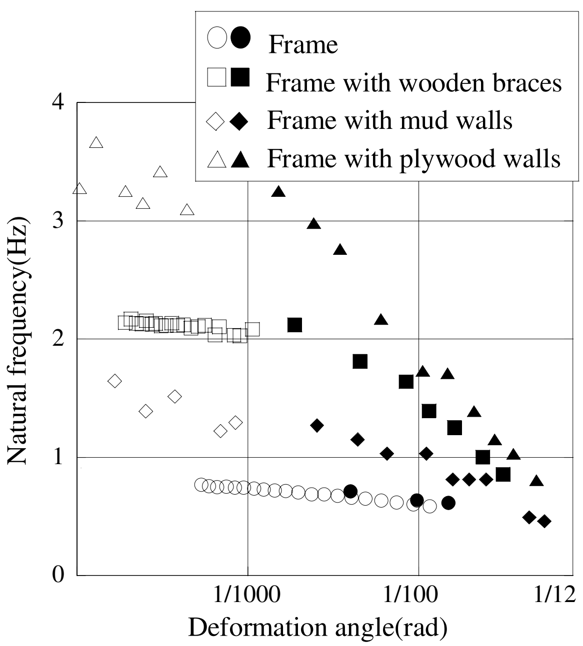


Fig.15 Equivalent natural frequencies.

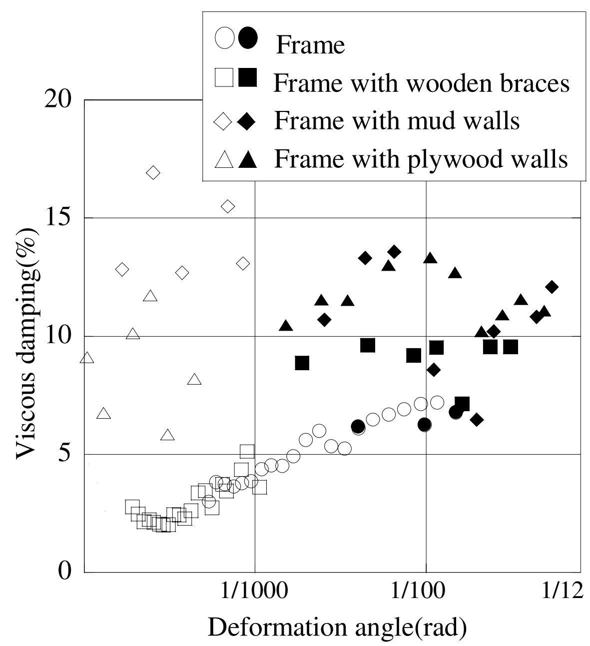


Fig.16 Equivalent damping factors.

response spectrum is calculated. The design criterion is that the maximum deformation angle must be less than the prescribed limit. This design method has been adapted by Suzuki et. al [2] for wooden houses. The procedures of the method are briefly described below.

(1) Unit frames are constructed according to the underlying wooden structure. For example, there are two unit frames for the frame of mud-walls: one is a frame with a seismic wall and another is a frame with a hanging wall, as shown in Fig. 17(a). Dynamic tests are carried out on every unit frame to obtain its skeleton curve of restoring force-deformation. Each skeleton curve is then approximated by an analytical model, such as a bi-linear model or a tri-linear model. Parameters are included in the model for each unit frame, such the wall thickness, section of the brace, the nail type to fasten the plywood, etc.

(2) The unit frames are integrated together to form each story of the wooden structure, and a skeleton curve is calculated for each story based on those of unit frames. Each story is then replaced by an equivalent SDOF system with its equivalent stiffness and equivalent damping factor calculated from the skeleton curve of the story.

(3) All SDOF systems representing all stories will be combined to form an overall SDOF system, which is equivalent to the entire structure. The equivalent stiffness and damping factor are determined for the overall SDOF system, and a skeleton curve is also calculated according to those of stories, as shown in Fig. 17(b).

(4) At each excitation level of the 1940 El Centro NS wave, a performance spectrum curve is calculated from the excitation acceleration response spectrum and the natural frequency and equivalent damping factor of the overall SDOF system. The intersection point of the performance spectrum and the estimated skeleton curve in step (3) gives a pair of force and deformation angle values, as shown in Fig. 17(c). This pair of values will be transformed back to the multi-story structure, leading to a point in the restoring force-deformation angle plane for the original wooden structure.

(5) Repeat step (4) for different excitation levels to obtain more points, then connect these points to constitute a skeleton curve for the wooden structure.

The above method was applied to the four specimens to obtain analytical skeleton curves of restoring force-deformation angle, as shown in Figs. 18(a) through (d). Also drawn in the figures are the test results for comparison. However, the deformation angles at different

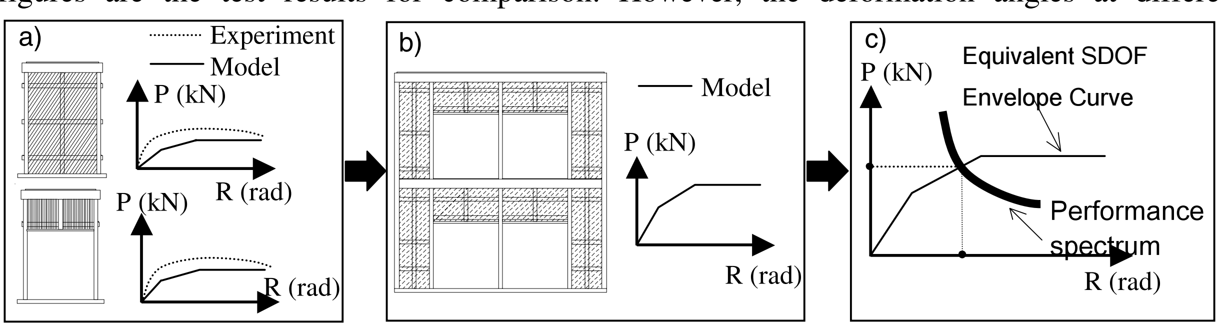


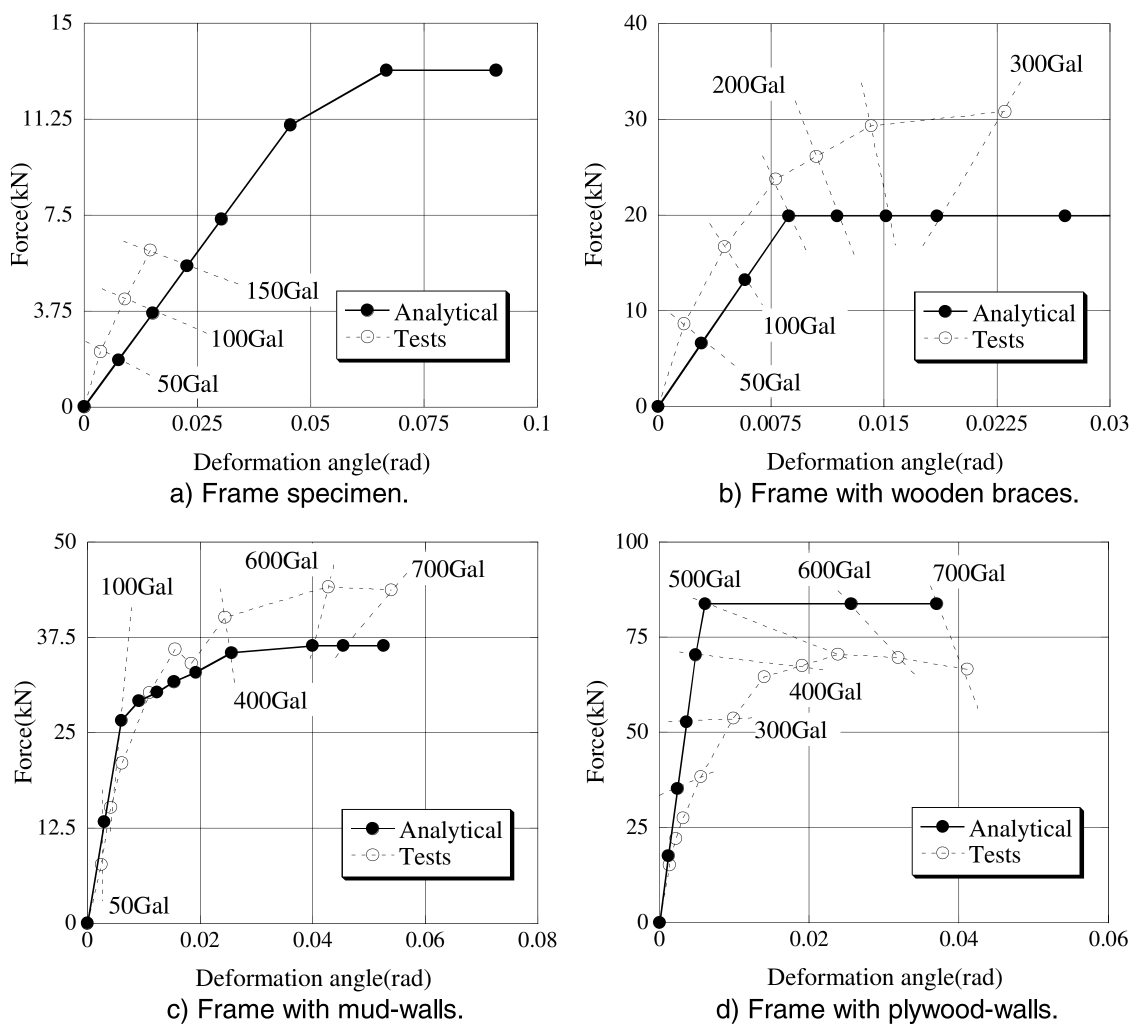
Fig.17 Schematic procedures of the response limit strength design method.

excitation levels of the two sets of results are quite close except in a range of the plywood-wall case. Therefore, the method can be used to estimate the deformation of a wooden structure at a certain excitation level. This is useful since the deformation is the most critical cause for wooden structure damages.

5. CONCLUSIONS

The results obtained from the destructive shaking table tests on full-scale two-story post-and-beam wooden frames show that the seismic performance of wooden structures will be significantly enhanced by adding seismic resistance elements, such as wooden braces, plastered mud-walls, and plywood-walls.

An analytical method based on seismic response spectra and equivalent SDOF systems are applied to the four test specimens. Comparison of the analytical results and the test results shows that the method is reliable in estimating large deformations of wooden structures under strong ground motions. Thus it can be used to seismic reinforcement design of existing wooden houses, as well as seismic design of new houses.



a) Frame specimen. b) Frame with wooden braces. c) Frame with mud-walls. d) Frame with plywood-walls.

Fig.18 Comparison of skeleton curves between analytical results and test result.

ACKNOWLEDGEMENTS

The authors are grateful to many students of Kanazawa Institute of Technology and Toyohashi University of Technology for carrying shaking table tests. Advices from Prof. G. Q. Cai of Florida Atlantic University, USA are also appreciated.

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