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FULL-SCALE COLLAPSE SHAKING TABLE TEST OF REMOVED AND RECONSTRUCTED HOUSE OF EXISTING WOODEN FRAME CONSTRUCTION HOUSE

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ABSTRACT

The authors have done a lot of static destruction loading tests of an existing dwelling wooden house as part of a study on the improvement of evaluation technology for seismic performance of wooden houses (Tsuda and Miyazawa, 2006; Tsuda and Miyazawa, 2005; Miyazawa et al., 2005; Tsuda et al., 2005). From those studies, it became clear that the existing house has a story shear strength coefficient of 0.2 at the story drift of 1/120 rad. and at the static collapse (when a building begins to collapse naturally), the limit story drift of an ordinary two-story light wooden building is 1/3 rad., the limit story drift of one-story house is 1/1.6 rad., and the limit story drift is 10~15 times of the story drift at the maximum strength. It is large ductility. However, there are many existing wooden houses without metal fasteners and these buildings show brittle destruction similar to a column base failing out on a wooden foundation during a severe earthquake. Structural specification, strength performance and deformability performance are different from an ordinary new house. Therefore, a two story wooden house that had been built in 1980, was transferred and rebuilt on the shaking table (great model high efficiency shaking table in Tadotsu engineering experiment station of the nuclear power generation technology mechanism), and the authors performed a trial to grasp the vibration behavior, deformability performance and a collapse process through the shaking table test by a recorded strong earthquake wave.

Introduction

The experimental study on a full scale collapse shaking table test and analytical study on three-dimensional elasto-plastic vibration analysis are explained in this report. In Chapter 1, the structural specification of the existing house and specimen on the shaking table test, and the experimental method are explained. In Chapter 2, results of four shaking table tests including the last collapse shaking table test are explained. Examination and consideration are described on the process of collapse from the experiment. In Chapter 3, an elasto-plastic 3-dimentional vibration analysis is described and results of the analysis are compared to the results of shaking table test in Chapter 2.

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Structural Specification of Specimen and Experimental Method of Shaking Table Test

Transfer and reconstruction of specimen

The specimen was transferred to and reconstructed on the shaking table from the site where the wooden house was built. The prototype of the specimen in the existing state will be called "existing house" in the following. The removed and reconstructed specimen from an existing house is called "reconstructed house". A little damage was given to the test piece by small excitation to adjust the vibration properties of the specimen as well as to the existing house through micro-tremor measurement.

Structural specification of the existing house

Fig. 1 shows the plan of an existing house where has built Sayama city in Osaka Prefecture. It was a two storied wooden frame construction house built in 1980. The floor space of the first floor and the second floor space were 47.8m^2 and 40.1m^2 respectively, and it was the house of a general scale at that time. The wooden braces of the section 27mm x 84mm ~ 90mm were used as a bearing wall. The groundwork of outside walls is wooden las (100mm x 9mm) and mortar finish, and moreover, the inner wall is mortar finish and gypsum board finish. This wall is effective bearing wall for the old Building Standard Law at the construction time, but, the bearing wall ratio for the necessary effective wall length is 0.37 times the present standard, so that, this building is illegal built to the present law (Table 2). Building Standard Law of Japan was greatly revised in 1981. Such a lot of existing illegal construction is remaining by revising several times of Building Standard Law, and there are a lot of houses where an earthquake-proof performance is insufficient and an earthquake retrofit is necessary.

Table 1. Structural specification of the existing house.

Item	Dwelling house	Finish of internal wall	Plasterbord, Cement plastering
Completion year	1980		Printed plywood
Construction method	2 Story frame construction	First floor area	47.8m^2
Bearing wall	Brace	Second floor area	40.1m^2
Roof	Roof tile	Total weight for seismic	276.9kN
Finish of external wall	Cement plastering	Average weight	3.15kN/m^2

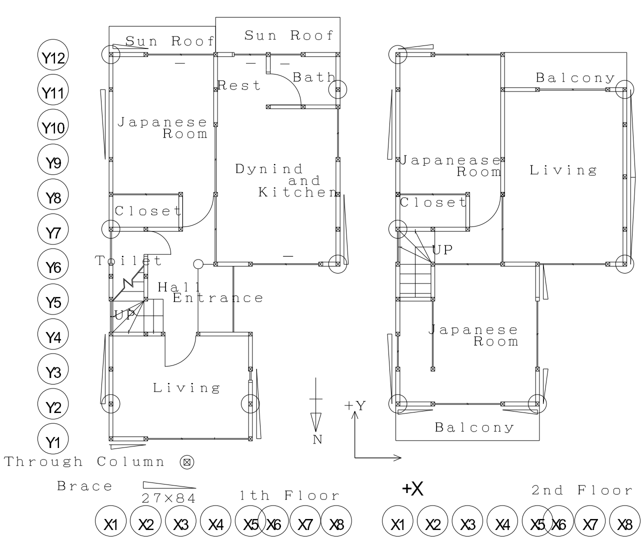


Figure 1. Existing house.

Table 2. Effective wall length.

	Direction	Standard at completion		Present standard	
		Wall length	Ratio*	Wall length	Ratio*
First story	X	12.15m	1.06	5.85m	0.37
	Y	33.08m	2.88	18.45m	1.17
Second story	X	10.80m	1.73	6.30m	0.72
	Y	37.80m	6.04	22.50m	2.57

* ;Ratio =Existing Wall Length / Neede Wall lLength

Photo 1. Existing house.

Structural specification of a reconstructed house

The specimen was accurately reconstructed in the existing house as much as possible, The decomposition of structural member was performed to the unit of the material to recycle the material of an existing house to the reconstructed specimen. The mixture ratio of mortar used to finish up the outside wall was determined from a general mixture ratio when the house was constructed (1980), in considering the compression test of two and four weeks. Wood, tiles, battledore bolts and floor joists (only in the Japanese-style room) of an existing house were recycled in the removed and reconstructed house, and mortar, tree las, wire las, plasterboard, nails and the anchor bolts were used in the new one. Moreover, a part such as the first floors is not reproduced. It was judged that the second floor was strength shortage in a perpendicular direction for the loading of a weight (live load and a part of dead load). Therefore, 12mm plywood was installed with N65 nails at spacing of 150mm as reinforcement. Because it was remarkably insufficient to be X direction brace, the wood brace of 0.9m length with a section of 120×32 that the top and bottom is reversed to existing wall in Y7-X2 on the line of X3. Therefore, the effective wall length rises from 5.85m to 7.20m and from 0.37 to 0.46 in the rate of the fulfillment of the effective wall length for the present regulation. The number and how to strike the nail at the end of a wood brace (included the nail on the column) followed an existing house. Moreover, it was nailed on the position different from existing nail hole, so that the reshoot of the nail causes strength shortage. The weight of a live load and a part of dead load was evenly distributed on the second floor of the specimen by using the channel type steel and sand.

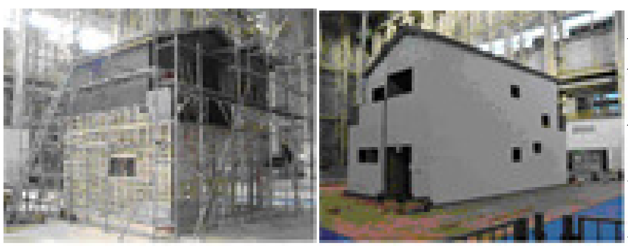


Photo 2. Reconstructed specimen.

Table 3. Input strong motion.

	Earthquake	Hrizontal	Vertical
No.1	JMA_KOBE Original 12/10 (0.7Hz-25Hz)	N-S 871cm/s^2	390cm/s^2
No.2	K-NET_Ojiya Original (0.7Hz-50Hz)	E-W 1334cm/s^2	818cm/s^2
No.3	JMA_KOBE Original (0.25Hz-25Hz)	N-S 817cm/s^2	332cm/s^2
No.4	JMA_KOBE Original (0.25Hz-25Hz)	N-S 817cm/s^2	332cm/s^2

( ) ; Frequency band of filter cut

Measurement and input strong motion for shaking table test

The story drift at the each story and the acceleration of the floor and the ceiling level are measured in the shaking table test. The story drift was calculated from the diagonal displacement that was measured by a displacement sensor (wire rolling type) between each floor. In addition, the story drift of the specimen until collapse was measured by using a laser image measurement system. Preliminary excitation and intended excitation were done as the experiment. Preliminary excitation is excitation for the purpose of closing the dynamic characteristics of the reconstructed house near to the existing house. Shaking table tests were done until collapsing by using the recorded earthquake wave shown in Table 3, and, after all, the experiment of excitation was done four times

Situation of change in natural period

In the existing house, the crack occurred on the outside wall finish mortar, and the aged deterioration of the mortar of the adhesion power between mortar and wood las was caused. The reproduction of this aged deterioration is difficult in the test piece making. Therefore, mortar was damaged by preliminary excitation (by the greatly decreased acceleration of the recorded earthquake wave) and the aged deterioration was reproduced. Reproducibility was judged by agreement of natural period between the existing house and the reconstructed house by the micro-tremor measurement. The first natural period of the reconstructed house is 0.15 seconds and reproducibility does not succeed. The first natural period of 0.17 seconds after the first preliminary shaking came up to 0.20 seconds after the second shaking.

Table 4. Change in the first natural period.

Existing house		0.19 sec
Specimen Reconstructed house	Befor the shaking test	0.15 sec
	After the first shaking test	0.17 sec
	After the second shaking test	0.20 sec

Full-Scale Shaking Table Tests

Results of shaking table tests from No.1 to No.4

It was not collapsed in the shaking table test No.1, though the X-direction story drift of Y1 frame line in the first story is 23.3cm, Y12 is 25.8cm, and the average is 24.6 cm (Table 5), The maximum average story drift of the first story is up to 1/11rad. (positive and negative are same, Fig. 2). The maximum residual story drift of the first story is as large as 1/60 rad. on the frame line Y1 shown in Table 5.

On the other side, the residual story drift of the second story is as small as 1/151 rad. At the time of the maximum in-put acceleration of 796cm/s^2 that is a first pulse wave and is the feature of the JMA_KOBE wave, the story drift becomes large in the positive direction and the story shear comes up to story shear strength, after then, the story shear decreases from the maximum strength by as much as 75%, afterwards, it pulls to a negative side greatly afterwards, it is returned, shear strength decreases from negative maximum strength by 40%, and the maximum response story drift is experienced in this shaking table test. At the time of a maximum in-put acceleration (889cm/s^2), the residual story drift was left on a negative side and it ended without greatly pulling in the following in-put acceleration wave. By this excitation, the displacement response of 1/252 rad. on the frame line X8 in the direction of Y was observed. The maximum response of the first story shear was 202 kN (shear coefficient is 0.92) in the positive direction and after then 104 kN (0.47) in the negative direction. The first story shear strength coefficient at the 1/120 rad. of the first maximum response is 0.46 in the negative direction. The acceleration response magnification was maximum on the frame line Y12 shown in Fig. 4.

In the shaking test No.2, the acceleration response magnification has decreased greatly compared with No.1 excitation as shown in Fig 4. The average response story drift of the first story was 1/16 rad. as shown in Table 5. In the shaking test of No.1, though the specimen entered the state of complete destruction, but in the No.2, the total collapse did not either. Therefore, it was judged that the collapse was difficult and had removed internal plasterboard and a part of wood lath of the first floor before excitation of No.3. In the No.3 excitation, the response story drift increased more in the negative direction than No.1. But, the total collapse did not either and the specimen has dangerously remained. The response displacement in this shaking test becomes the maximum from No.1 in No.3, in a negative side greatly, and is thought immediately before the collapse. The residual first story drift exceeded 1/15 rad. and the specimen remains without the total collapse where the limit displacement is greatly to be 1/9.3rad.

Finally, the specimen collapsed in No.4 excitation. At the time of a maximum in-put acceleration of a shaking table, the specimen suffered large vibration in a positive and negative direction shown in Fig. 5, and after the time of 6.5 second, the specimen vibrates in negative direction. At about 7.3 seconds (in-put acceleration is 713cm/s^2 and first story drift is about 1/6rad.), the pull return force to a positive direction is shortage, and began to collapse. And then, it is thought that it greatly distorts and become to collapse into a negative direction at the time of 7.87 seconds.

Table 5. Maximum response.

Test No.	Ground Mortion	Maximum response		
	Acceleration	Acceleration of the second floor	First Story Drift	Story shear coefficient of the first story
No.1	889 cm/s^2	1030 cm/s^2	24.6 cm	0.92
No.2	1435 cm/s^2	248 cm/s^2	17.4 cm	0.16
No.3	852 cm/s^2	188 cm/s^2	34.8 cm	0.16
No.4*	852 cm/s^2	215 cm/s^2	95.4 cm	0.21

* Maximum data is value untill 8.0 seconds in No.4 test

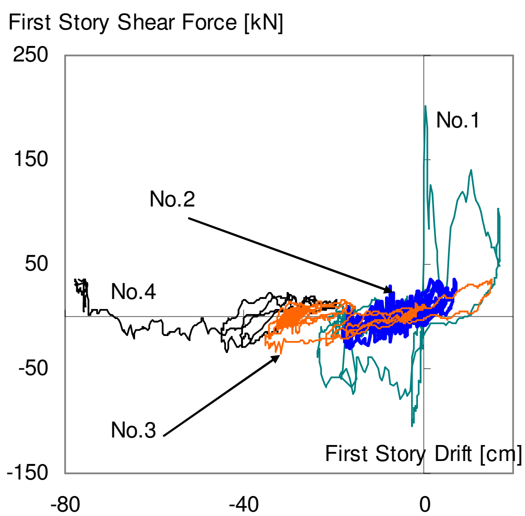


Figure 2. First story shear-story drift

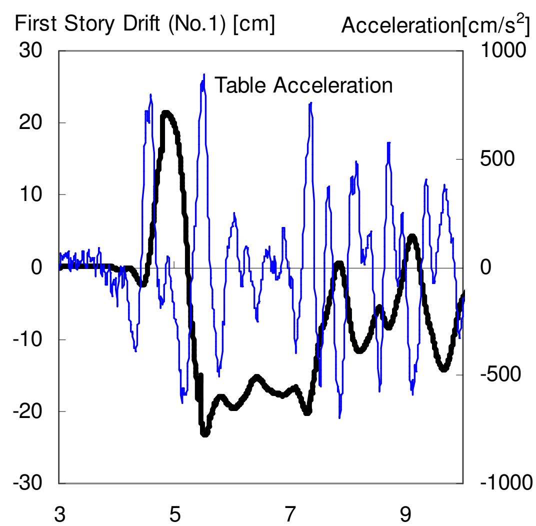
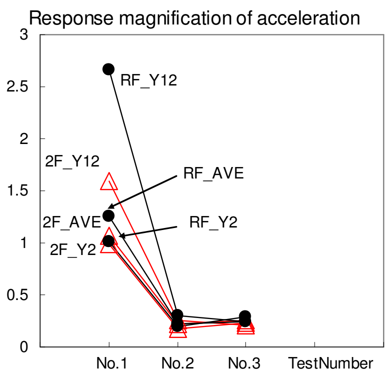
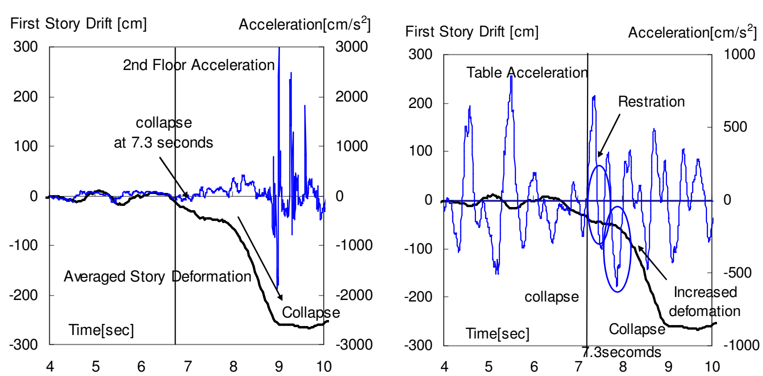


Figure 3. Response of first story drift (No.1).



Acceleration

Figure 4. Response magnification.



Acceleration

Story drift

Figure 5. Collapse process (No.4).

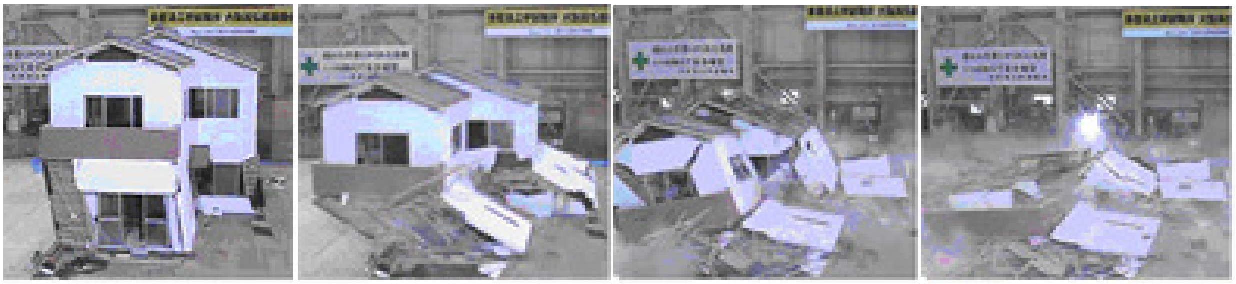


Photo 3. Collapse process (No.4).

Analytical Study

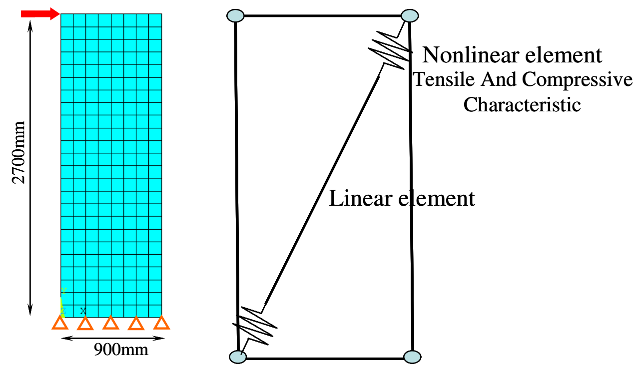
In this chapter, we analytically examine a vibration property and a process of collapse of the reconstructed house reported in Chapter 2. The 3-dimensional elasto-plastic analysis was adopted for analytical investigation.

Analytical model and analysis method

The horizontal force resistance elements of the reconstructed house are wooden brace, column with spandrel and hanging wall, plasterboard wall, mortar finish, and wooden lath. As the analytical object is the reconstructed house, the experimental study on each bearing wall element is not conducted. Therefore, each bearing wall element analyzed by static elasto-plastic finite element method, and the force-displacement relationship obtained from analysis is used for a 3-dimensional analysis.

(1)The shear force - story drift relationship and shear strength of each bearing wall
The mortar finish used to finish up an inside and outside wall is not a bearing wall as Building Standard Law, but is thought that the horizontal strength is actually large. Therefore, the analytical model was made from a compression test result of the test piece of the mortar used for the reconstructed house and in consideration of the influence of the crack on the specimen by preliminary excitation. Mortar was modeled as a nonlinear material characteristic (though logic was lacked). The axial wooden elements are assumed to be elastic beam element. An analytical result of the wall element is used for the 3-dimensional elasto-plastic analysis of total structure. Similarly, the bearing wall with a brace was statically analyzed in considering the stiffness and strength at a join. An analytical model of wooden lath and the gypsum board in consideration of the shear force - story drift curve research data in the past.

(2)Model of 3-Dimensional Elasto-plastic Analysis
An analytical object is consisted of the columns, beams and bearing walls. And, the column and the beam are treated as a beam element and each bearing wall is treated as an equivalent substituted brace model in the 3-dimensional elasto-plastic analysis. The bearing wall is modeled as an equivalent substituted brace by the shear force - story drift curve obtained by the above-mentioned elasto-plastic analysis in Fig. 7. Moreover, to consider the effect of the column with spandrel and hanging walls, the brace model is divided into three steps of upper, middle and under parts. Using this equivalent brace model, the total wall frame was modeled as substituted brace model with joint part of denting stiffness and tensile stiffness as shown in Fig. 8. The weight of the building is distributed on each floor level in the vibration analysis. The 3-dimensional elasto-plastic analysis was done by the displacement increment of the β method of Newmark. "RUAUMOKO 3-Dimensional Version" (Carr 2000) was used as the analytical software.



Cement plaster wall model

Brace wall model

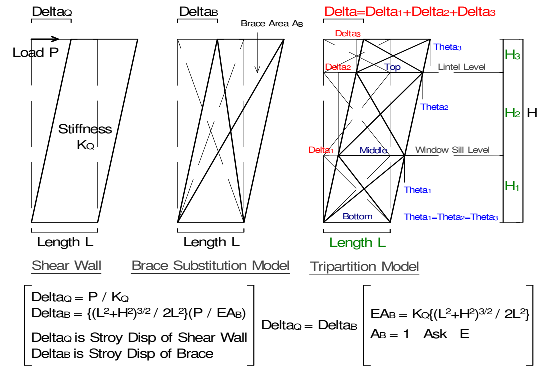


Figure 7. Substitution brace model.

Figure 6. Analytical model of bearing walls.

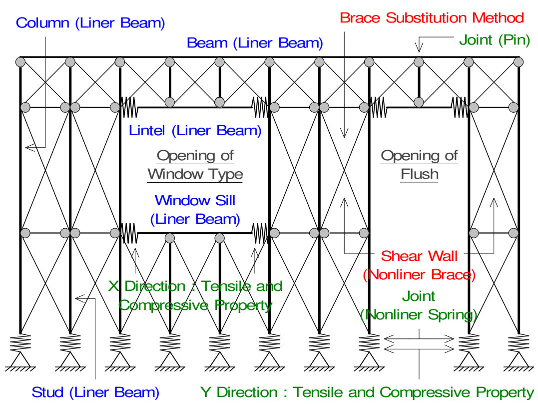


Figure 8. Constitution of the wall.

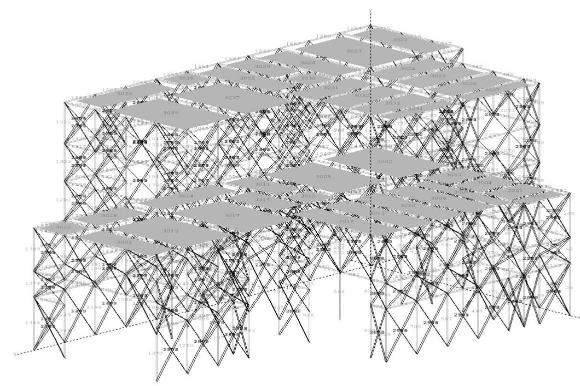
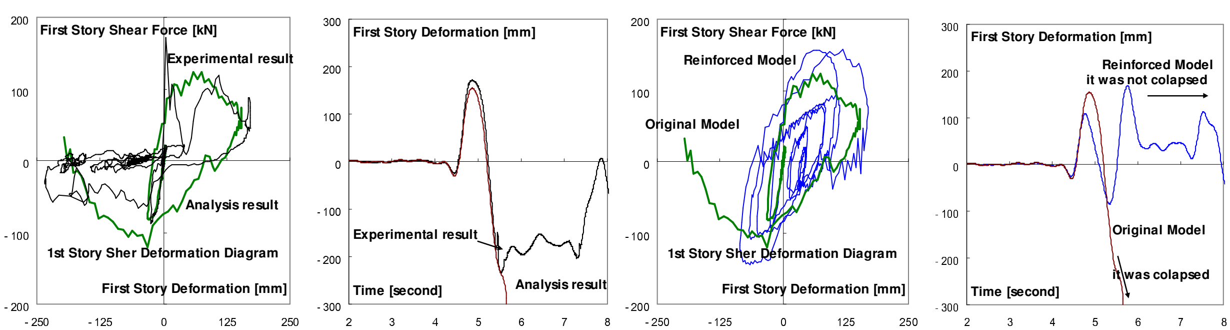


Figure 9. Three Dimensional Elasto-Plastic Model.



First story shear-story drift diagram

Response of first story drift

First story shear-story drift diagram

Response of first story drift

(1) Reconstructed house

(2) Reinforced Model

Figure 10. Result of vibration analysis.

Result of Analysis

The analysis corresponding to the shaking table test of experiment No.1 of Chapter 2 was done by the above-mentioned analytical model. The seismic wave that adjusted the maximum acceleration of the JMA_KOBE wave to 120% was used as an earthquake input. Moreover, the acceleration wave measured on the shaking table of experiment No.1 of Chapter 2 was used for the analysis. Fig. 10. shows an analytical result of the shaking table test No.1. The maximum response of first story shear is 122kN in the positive side, and the story shear coefficient is about 0.45 according to an analytical result. An analytical result indicates that the maximum story shear is on a positive side as well as the experiment, and the story shear decreases up to about 36% afterwards. The story drift at that time is about 1/2rad. then, the specimen displaces to the negative side and becomes the maximum response of story shear 120 kN in a negative side, and it becomes a collapse as story shear strength decreases. The tendency until collapse was possible to consent to be understood though there was a difference in the story shear strength of the analysis and the experimental result. In addition, the collapse limit (point that the story shear strength becomes 0 in the analysis) of the analysis is 1/1.6rad. It is roughly corresponding to an analytical result, though the point that had begun to collapse was defined as the collapse limit in the experiment. However, the specimen doesn't collapse in the shaking test No.1, but after then, it collapsed in the shaking test No.4.

Examination of earthquake-retrofit by an analytical method

Next, the structural safety and possibility of collapse by an earthquake-retrofit are examined by an analytical investigation. The reinforcement was made using plywood and wooden braces that are used as an ordinary earthquake-retrofit for a lot of wooden dwelling houses. Reinforcement assumed only the first floor to target that the ratio of the effective wall length /necessary wall length demanded by the law of earthquake-retrofit becomes about 1.0 roughly. Fig. 10 shows an analytical result of earthquake-retrofit. The maximum story shear strength and an equivalent rigidity have changed greatly by an earthquake-retrofit. In particular, the earthquake-retrofit specimen does not collapse and the response has ended, though a large deformation is caused on a positive side in the analysis.

Conclusions

An analytical model consisting of beams, columns and an equivalent substituted brace of three steps by using the shear force - story drift curve is solved by elasto-plastic analysis. It can be judged that the proposal analysis model roughly gets response behavior of each part and whole structure of the specimen in the shaking table test until collapsing by this analysis. However, it is thought that an analysis based on large displacement theory is needed for the investigation of a complete collapse.

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