E-DEFENSE EXPERIMENTS ON FULL-SCALE WOODEN HOUSES

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ABSTRACT :

In order to clarify the collapse process of wooden houses, and to validate the effect of seismic diagnoses and seismic retrofits, a five-year research project named "A Special Project for Earthquake Disaster Mitigation in Urban Areas" is conducted by the Ministry of Education, Culture, Sports, Science and Technology from 2002-2007 in Japan. The main research item in the last two year was full-scale shake table tests using E-Defense, which is the largest shake table in the world. Shake table tests in E-Defense were conducted on the full-scale Japanese post-and-beam type wooden houses using more than 10 test models including traditional type Japanese wooden houses. In this paper, the experimental results by E-Defense will be described. The test results showed that the seismic resistance capacity of wooden houses built before the current Japanese Building Standard was very low, but the appropriate seismic retrofits based on the current seismic diagnosis method would improve the capacity so as not to collapse by the input motion recorded in 1995 Kobe Earthquake. The results also showed that the aging effects may affect the seismic capacity of the wooden houses.

KEYWORDS: E-Defense, Shake table test, Collapse behavior, Seismic retrofit

1. INTRODUCTION

Seismic performance of Japanese wooden houses were improved by the revised Japanese Building Standard Law in 1981, and it is known that the damage of wooden houses built according to the law was not so large even in the 1995 Hyogo-ken Nambu Earthquake (Kobe Earthquake). However, the wooden houses built before 1981 were severe damaged and cause a lot of the victims in the Kobe Earthquake. There are still a lot of wooden houses in Japan which do not satisfy the required seismic capacity in the revised law, and they are concerned to cause a serious seismic disaster by a destructive earthquake. In order to mitigate the seismic disaster caused by the damage of wooden houses, it is important to clarify the seismic performance and failure process of the existing wooden houses, and to apply the suitable reinforcement to improve the seismic performance.
From 2002 – 2007 of Japanese fiscal year, a five-year research project named "A Special Project for Earthquake Disaster Mitigation in Urban Areas" was conducted by the Ministry of Education, Culture, Sports, Science and Technology in Japan [Sato, M. and Inoue, T., 2004]. One of the subjects in this research project is the improvement of the seismic performance of wooden structures [Minowa, C. et al, 2004, Nakamura, I., et al, 2006]. The schedule and the research subjects conducted in the project is shown in Table 1. In this program, the first three years are for the preliminary studies [Koshihara, M., et al, 2004, Tsuchimoto, T., et al, 2004, Irie, Y., et al, 2004, Miyake, T., et al, 2004, Shimizu, H., et al, 2008], and the last two years are for the shake table test using E-Defense. Shake table tests were conducted on the full-scale Japanese post-and-beam type wooden houses using 15 test models including traditional type Japanese wooden houses. These test models were classified following three types: The conventional Japanese post-and-beam type wooden houses (hereinafter "the conventional wooden house"), the traditional wooden houses, and the wooden house which was once

experienced the excitation and rehabilitated (hereinafter "the rehabilitated wooden house"). In the tests for the conventional wooden houses, four test models were used in total. Two test models which were actually used for the residential house were used for the shake table test in 2005. Additional two newly-built test models were used in the excitation tests in 2007 to compare the difference of construction date. In the tests for the traditional wooden houses, 10 test models were used. In 2005, two test models of the traditional urban houses were used to obtain the behavior and damages of such houses under strong seismic motions as a whole houses. In 2007, the excitation tests with more simply models were conducted using eight test models. The purpose of the tests in 2007 was to investigate the problems such as the influence of stiffness property of horizontal plane, the relation with the rigidity of horizontal plane and the eccentricity ratios, the influence of slipping phenomena of the unfixed column. In the tests for the rehabilitated wooden houses, one test models was used for the test. The test model was once experienced the excitation test, and used again with the seismic retrofit. The purpose of the test was to confirm the seismic performance of the retrofitted wooden houses. In this paper, the experimental results for the conventional wooden houses are described.

2. OUTLINE OF E-DEFENSE

The excitation tests were conducted in E-Defense. "E-Defense" is the nickname of the world-largest

Table 1 Schedule and research subject

Research Subjects	Japanese fiscal year				
	2002	2003	2004	2005	2006
Shake table tests by E-Defense					
Earthquake response observation of existing wooden houses					
Investigation of aging effects of existing wooden houses					
Horizontal loading tests of wood frames					
Middle-sized shake table test					
Development of PC simulation method tracking the collapse behavior of wooden houses					

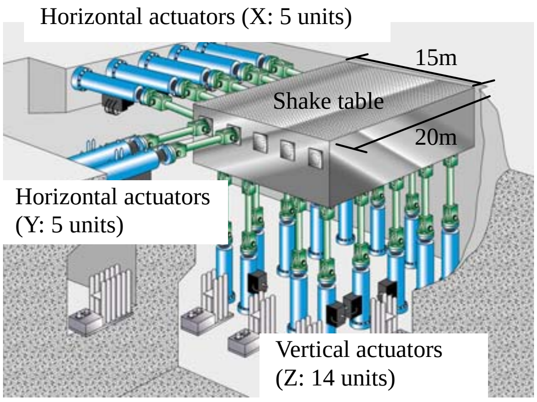


Fig.1 Shake table of E-Defense

Table 2 Major specifications of E-Defense

Payload	12MN (1,200tonf)	
Table size	20m x 15m	
Shaking direction	Horizontal X, Y	Vertical Z
Max. acceleration*	900Gal	1,500Gal
Max. velocity	2 m/s	0.7 m/s
Max. displacement	+-1 m	+-0.5 m
Max. allowable moment	150 MN-m (at vertical 9.8m/s^2 shaking)	40MN-m (at max. horizontal acceleration)

* At the maximum payload

three-dimensional full-scale earthquake testing facility of National Research Institute for Earth Science and Disaster Prevention (NIED), Japan [Kajiwara, K., et al, 2006]. The testing facility was constructed to investigate the damage of structures under three dimensional strong earthquakes after the 1995 Kobe Earthquake, and started its operation from April 2005. Figure 1 shows the shake table and the actuators, which are the main part of the facility. The specification of shake table is shown in Table 2. The testing facility has ability of reproducing the seismic motions recorded in the 1995 Kobe Earthquake with a 12MN weight.

3. EXCITATION TESTS ON CONVENTIONAL WOODEN HOUSES

3.1 Test Models

The objects of the experiments on the conventional wooden houses are to clarify the collapse process of wooden houses, and to validate the effect of seismic diagnoses and seismic retrofits. In order to investigate the seismic performance of non-conformed conventional wooden houses, two existing wooden houses built before 1980 were used as the test models. They were two-story wooden houses built in 1974 in a Japanese city, and were dismantled to use for the excitation tests (Hereinafter these test models referred as "Model A" and "Model B"). They originally did not satisfy the seismic performance required in the current building code. In order to compare the response under large earthquakes between the condition with and without seismic reinforcement, seismic retrofits were applied to Model B, and nothing was done on Model A. In addition to these models, two test models, which named "Model C" and "Model D" were newly constructed and used for the excitation tests. Model C and Model D simulated the plan and the timber framework of Model A. The seismic reinforcements applied to Model B and Model D were mainly three types of reinforcement, that is, wood braces, plywood, and joint metals. Less joint metals were used in Model D compared with Model B. Model D had the concrete basement and the model of soil layer simulated by the polystyrene foam. The seismic diagnosis and the seismic reinforcement applied to the test models followed the method determined in the guideline in Japan [The Japan Building Disaster Prevention Association, 2004]. The guideline indicates that the seismic performance assessment score calculated according to the guideline should be over 1.0 to satisfy the requirements of seismic performance in current Japanese building law. The seismic performance scores of Model A and C were both about 0.5. The score of Model B was improved to 1.84 with the seismic reinforcement, which was originally about 0.5 as same as Model A. The score of Model D was about 1.54. The mainly specification of Model A are listed in Table 3, and the difference of these test models are listed in Table 4. The plan of Model B is shown in Fig. 2.

The collapse tests were planned in the excitation tests. Because the shake table of E-Defense can move maximum 2m in peak-to-peak in horizontal direction, there is a gap about 1.5m~3.5m around the table. Thus, a guard pedestal made of steel frames was set on the shake table to cover the gap and to protect the table and the shake table system like actuators or servo valves not to be damaged by the collapsed test models. The size of the guard pedestal is 22.85m x 27.85m, and the weight is about 2200kN. All test models were set on this guard pedestal. Response acceleration and response displacements at several locations on shake table, each floors, and roofs were measured in the tests using about 300 sensors. These data were recorded with a 200Hz sampling frequency after processing with an analogue low pass 30Hz filter. The measurement method using image processing technique [Fujita, S., et al, 2004] was also used to measure the large response displacement caused by the collapse behavior. 13 CCD cameras were set outside of the models to observe the collapse behavior.

Table 3 Specification of Model A

Structural specification		Post-and-beam wooden houses	
Construction time		1974	
External wall	Exterior	15mm thickness Mortar with metal lath on wooden lath	
	Interior	Mud wall, 50mm thickness	
Inside wall		Mud wall, 55~60mm thickness	
Seismic resisting elements		Mud wall Wood brace, 90mm x 30mm	
Roofing		Clay tile roofing, without roof mud	
Ceiling		Printed plywood or finished gypsum board	
Floor		*Tatami* or flooring	
Dimension (mm)		5,820 (W) x 5,940 (D) x 7,147 (H)	
		1st story	2nd story
Seismic Weights (kN)		119	91
Height of story (mm)		2760	2645

Table 4 Test models for excitation tests on conventional wooden houses

	Construction year	Plan and wooden framework	Seismic retrofits	Seismic performance score*
Model A	1974		None	0.50
Model B		Almost the same as Model A	Wooden braces, plywood, joint metals	1.84
Model C	2006	Simulate Model A	None	0.49
Model D		Simulate Model A	Wooden braces, plywood, joint metals less than Model B	1.57

* In the first story, Y direction

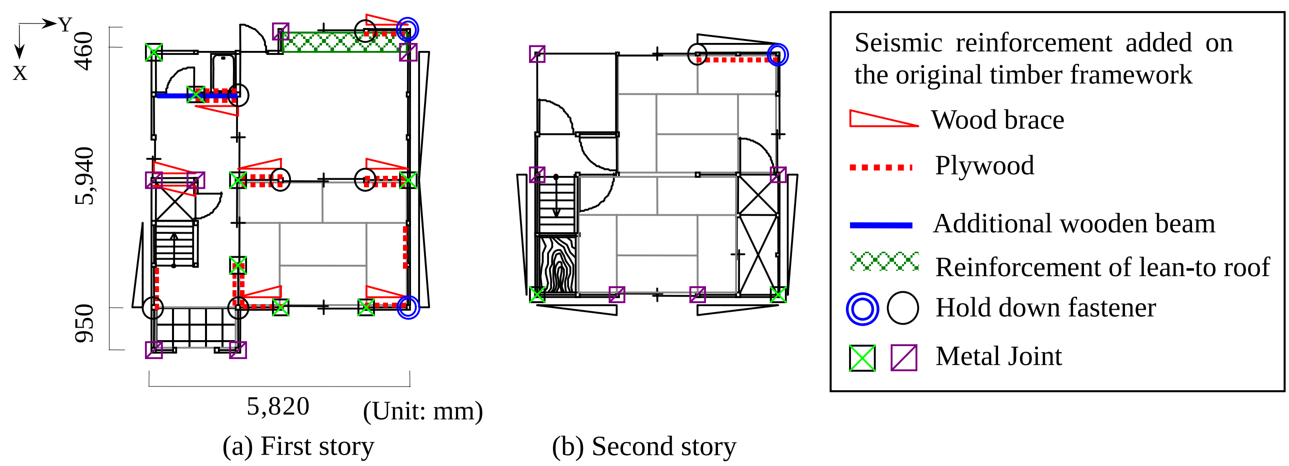


Fig.2 Plan of Model B

3.3 Excitation Test Results and Discussion

The applied input motion was the seismic motion recorded at JR Takatori station in the 1995 Kobe Earthquake [Nakamura, Y., et al, 1996]. The input level, direction, and the test results are summarized in Table 5. Model A, without reinforcement, collapsed from its first story soon after starting the excitation by the first 100% JR Takatori input motion, but Model B, with reinforcement, withstood the excitation. Model B did not collapse by the additional 60% JR Takatori input motion which assumed the aftershock. It collapsed by the second 100% JR Takatori input motion. Model C, which simulated the plan and timber framework of Model A, withstood the excitation by the first 100% JR Takatori excitation, and collapsed by the second 100% JR Takatori excitation, as same as Model B. Model D, which simulated Model A and applied less seismic reinforcement compared with Model B, withstood 100% JR Takatori excitation three times, and collapsed at the fourth time excitation. Figures 3(a)-(d) show the models after the first 100% JR Takatori excitation, and Figs. 4(a)-(d) show the load-displacement relerionships of these models at the first story in Y-direction. As shown in Fig. 4, Model A, B, and C reached their maximum strength at the first 100% JR Talatpri excitation, but the share force of Model D did not reach its maximum strength. The maximum strength of Model D was about 230kN at the second 100% JR Takatori excitation. The maximum share force of Model A was about 131kN, and that of Model B was about 201kN. Considering that they originally had almost the same timber framework, the strength of the model improved about 1.5 times by the applied seismic reinforcement. It shows that the current seismic diagnosis and the reinforcement method is effective to prevent the non-conformed wooden houses from collapse. The maximum share force of Model C was about 140kN. It was a little larger than that of Model A, and Model C did not collapse at the first 100% JR Takatori excitation. But it can be said that the model was very close to collapse, because the maximum story drift reached about 1/6rad, and from Fig. 4, it can be seen that the strength was almost lost. Compared with Model A and Model C, it shows that the newly built model showed better seismic performance than the model actually constructed in the past time. The test results show that the seismic capacity

Table 5 Test results of the excitation tests on conventional wooden houses

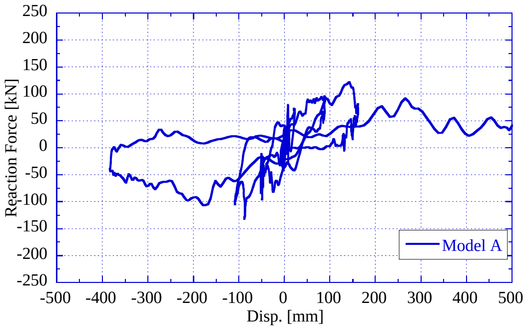
Input motion*	Max. acc. [Gal] of each input direction**			Test result			
	X	Y	Z	Model A	Model B	Model C	Model D
JR Takatori 100% #01	666 (EW)	642 (NS)	290 (UD)	Collapse	Withstood	Withstood	Withstood
JR Takatori 60%	340 (EW)	385 (NS)	174 (UD)	---	Withstood	Withstood	Withstood
JR Takatori 100% #02	666 (EW)	642 (NS)	290 (UD)	---	Collapse	Collapse	Withstood
JR Takatori 100% #03	666 (EW)	642 (NS)	290 (UD)	---	---	---	Withstood
JR Takatori 100% #04	666 (EW)	642 (NS)	290 (UD)	---	---	---	Collapse

* Only the excitations by the seismic input motion were listed. White noise excitation and sweep excitation were conducted to obtain the characteristics of the test models.

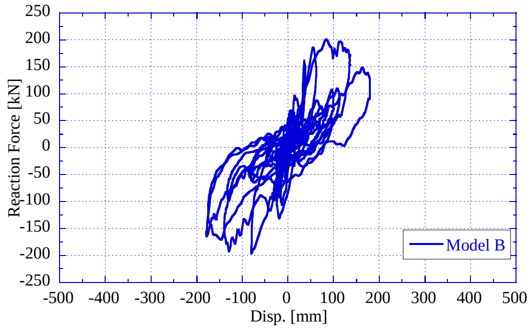
** X: shorter direction of the shaking table, Y: Longer direction of the shaking table, Z: vertical direction. The input direction for the test model is drawn in Fig. 2.

(d) Model A (c) Model B (b) Model C (a) Model D

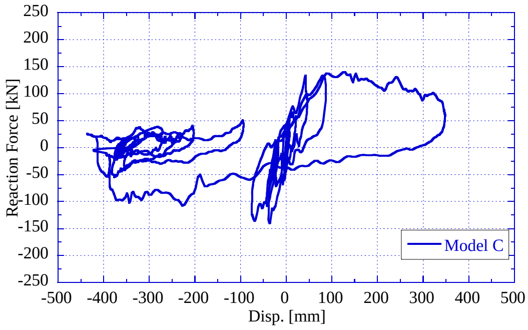
Fig. 3 Damage of each model after the first 100% JR Takatori excitation



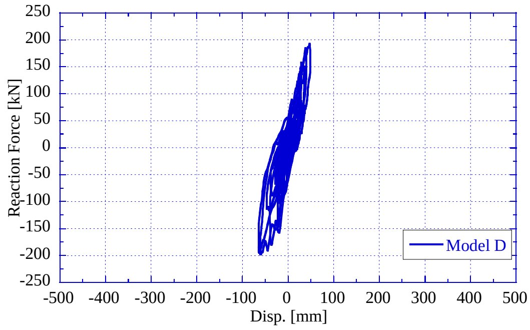
(a) Model A



(b) Model B



(c) Model C



(d) Model D

Fig. 4 Load-displacement relationship of each model after the first 100% JR Takatori excitation

of the non-conformed wooden houses was very low, especially if it constructed actually in the past time. One reason of the difference of Model A and Model C is considered to be due to the aging. In addition, from the results of loading tests for walls showed that the difference of construction method itself was also considered to affect the result of the excitation test. Compared with Model B and Model D, Model D showed better seismic performance compared with Model B, though the calculated seismic performance of Model D was less than that of Model D. One possible reason is the difference of the original seismic capacity of timber framework itself, as shown in the test results of Model A and Model C. From the series of the excitation test, it can be said that the effect of aging should be counted in the seismic diagnosis applied to the wooden houses actually built in the past time. The effects of the simulated soil layer, or the concrete basement on the response of Model D were not clear.

4. CONCLUSION

The five-year research project for improving the seismic performance of Japanese wooden houses were conducted from 2002-2007. As part of the research project, the full-scale shake table tests for wooden houses were conducted by E-Defense. E-Defense showed enough ability to collapse completely the full-scale wooden houses, and the facility is useful for verification of the seismic design or diagnosis for wooden houses. From the results of the excitation tests on the conventional wooden houses, it showed that the current seismic diagnosis and the reinforcement method is effective to prevent the non-conformed wooden houses from collapse. The results also showed that the aging effects may affect the seismic capacity of the wooden houses. The excitation tests for reconstruction models provided the practical data of non-conformed wooden houses.

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