VERIFICATION OF SEISMIC REINFORCEMENT ON OLD WOOD HOUSES BY USE OF E-DEFENSE

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ABSTRACT:

Many of the existing old wooden houses in Japan are not enough strong to resist the strong earthquake. It is necessary for the houses without sufficient seismic performance to be repaired and improved in order to save the resident lives and properties. It is difficult to evaluate the existing old wooden houses, because the old houses have not only various construction methods and specification, but deterioration and degradation. So, the 2 houses with the same construction method, specification, and floor area each other were advertised for public, selected, and subjected to the shaking table tests. The 2 houses were divided into some parts, brought, and reconstructed at E-defense of NIED. The one of them were reinforced and tested, the only divided parts of the other house were repaired and tested.

As a result, the building without reinforcement collapsed in several seconds, and it could be said that the damages of wood houses caused by Hyogo-Nambu Earthquake in 1995 was reproduced. On the other hand, the house with seismic reinforcement of the precise diagnosis criticism point 1.5 didn't collapse though damages were taken in several parts. These were compared with the estimated values depending on the several seismic diagnosis in "Methods of seismic diagnosis and reinforcement of wood houses" [1], and it was clarified that the estimated values were in the safe side.

KEYWORDS: Seismic diagnosis, Seismic Reinforcement, E-Defense, Old wooden house

1. INTRODUCTION

As a part of "Experimental study of wooden buildings" of the Special Research Project on Earthquake Disaster Mitigation for Metropolis, started in 2002 by Ministry of Education, Culture, Sports, Science and Technology (MEXT), the several wood houses have been subjected to the shaking table tests. This paper reports a shaking table test of two wood houses, which were collected from the public, divided, carried, and reconstructed on the 3-D Full-Scale Earthquake Testing Facility (hereinafter referred to as "E-Defense") of the National Research Institute for Earth Science and Disaster Prevention (NIED). The one of two houses was tested as it was, the other was tested after seismic reinforcement in order to confirm the performance of the seismic reinforcement.

2. OBJECTIVES

The objectives of the test were to understand the collapsing behaviors of actual old wood houses under strong earthquake and to verify the methods of seismic diagnosis and reinforcement described in the "Methods of seismic diagnosis and reinforcement of wood houses" 1) (supervised by the Housing Bureau of the Ministry of Land, Infrastructure and Transport, and issued by the Japan Building Disaster Prevention Association), which was revised at 2004.

3. Overview of The Tested Houses

Houses to be reconstructed and subjected to the shaking table test were collected from the public. Of over 200 houses, the two houses which were satisfied with the conditions, as mentioned above, were the same in the built year, structures and specifications, and were located on the site which had spaces for executing dividing works were selected. The selected houses were two about 30-years old two-storied wood post and beam houses built in Akashi City, Hyogo (hereinafter referred to as Akashi Houses A and B). Exterior and interior views of the houses are shown in Photo. 1 and 2, and plans and elevation views are shown in Figs. 1 and 2, respectively. The left side in Photo. 1 was House A. The specifications of each part are shown in Table 1. The houses were slightly different from each other due to improvement works, but had almost the same room arrangement. The houses were typical wood houses built in the Kansai District in this period.

Photo. 1 Exterior view of tested house.

Photo. 2 Interior view of tested house.

Table 1. Specifications and finishing materials of Akashi Houses

Part	Specifications and finishing materials
Roof	Japanese roof tiles on covered soil
Exterior wall	Lath mortar, on wood lath base
Interior wall	*Juraku* plastering, soil plastering
Ceiling	Decorated gypsum board, printed plywood (Japanese rooms)
Floor	*Tatami*, flooring
Bathroom	Tiles (House B), unit bath (House A)

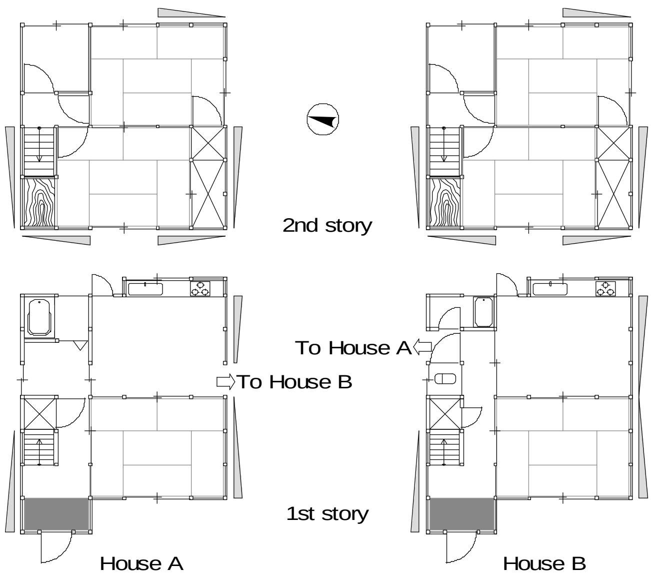
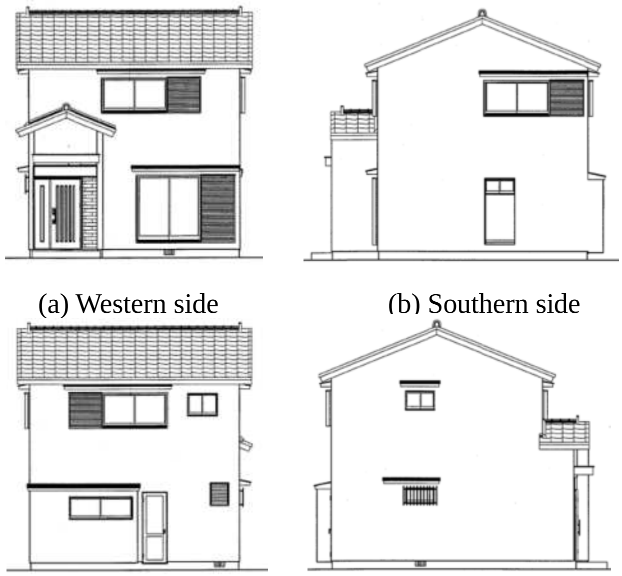


Fig. 1. Plans of Akashi Houses

Note: shows the actually found braces.



(a) Western side (b) Southern side (c) Eastern side (d) Northern side

Fig. 2. Elevation of Akashi Houses

4. Method of Reconstruction

The houses were moved and reconstructed based on the following concepts:

1) Since the houses were to be transported on roads, the houses were to be divided into parts not exceeding a width of 3.3 m and a height of 3.8 m, which are required by the Road Traffic Law.
2) The walls along the axis of main vibration (north-south direction in Fig. 1) were to be not damaged as much as possible.
3) The houses were cut at points other than joints, since disassembled joints are difficult to reassemble so as to have the original performances. The cut parts of the members were designed and jointed to restore the original strength of the members.
4) Since parts constructed by the wet construction method are difficult to restore so as to have the original performances, cutting the parts was minimized. The cut parts of the wet construction method were to be restored so as to have the original shear performance as much as possible.
5) The houses were cut through openings that had relatively low shearing resistance and were restored so as to have the original shear performance as much as possible.

Based on these concepts, the houses were cut, divided to four portion and transported to the E-defense. The removing and reconstruction procedures involved 1) cutting the exterior and the interior wall, 2) reinforcement of the walls with plywood for transporting the houses (Photo. 3), 3) cutting the structural frame and jacking up the houses, 4) lifting and loading the part of the house onto trailers (Photo. 4), 5) reconstructing the houses, 6) repairing the cut members (Photo. 5), 7) restoring the floor and installing live loads, and 8) restoring the exterior mortar wall and filling the interior walls. The houses set on the shaking table are shown in Photo. 6. The microtremors were measured before and after the reconstruction of Akashi Houses, and the results are shown in Fig. 3. The measurements showed that the reconstruction made the initial stiffness a little bit low in consideration of the effects of the decline in the weight of the houses.
However, depending on the many research experience and results, we thought that the ultimate performance of the house didn't take the influence of reconstructing works, even if the natural frequencies had decreased.

Photo. 3. Reinforcement for transporting.

Photo. 4. Lifting and transporting.

Photo. 6. House specimens set on a shaking table.

Photo. 5. Repairing the cut beams.

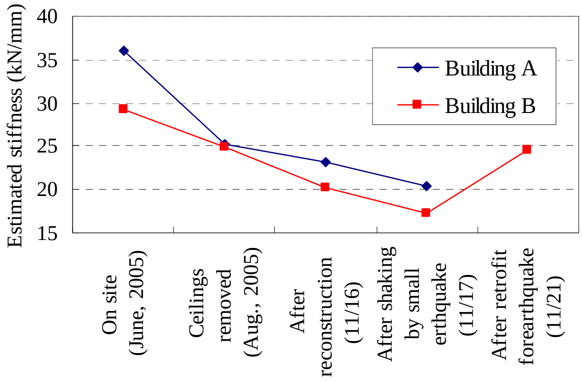


Fig. 3. The Stiffness of the tested houses estimated from weights and dominant frequencies of microtremor.

5. Seismic Diagnosis

The scores of seismic diagnosis of Houses A and B were evaluated by the several seismic diagnosis methods.

1) General seismic diagnosis

The score of general seismic diagnosis; I_{wg} were defined by the equation (1) with required strength; *Qr*, strength of walls; *P*, reduction factor of seismic element arrangement; *E*, and reduction factor of deterioration; *D*.

$$I_{wg} = P \times E \times D / Q_r \quad (1)$$

The score of general seismic diagnosis shows Table 2. The scores of 1st story in the main shaking direction of Houses A and B evaluated by the general seismic diagnosis were the same 0.62 without reduction factors of deterioration. The reduction factors of deterioration, *D* were calculated by the followings.

1) When the parts exist in the building, the points of the existing parts are counted. Then the total of the points, D_e, are calculated.
2) When the deterioration phenomena are recognized visually, the points of the deteriorated parts are counted. Then the total of the points, D_d, are calculated.
3) Calculating the reduction factors of deterioration with the equation (2)

$$D = max\left\{1 - \frac{D_d}{D_e}, 0.7\right\} \quad (2)$$

The deterioration phenomena include the aging, color changing, discoloration, corrosion, rot, decay,

termite attack, moss, or mold of materials, gap, rolling up, peeling, crack, breaking, or failure of members, deterioration in sealing or gap in joints of sheathing members, water soaking mark of the floor or ceiling, or decline, excessive vibration, or sound of floor. When one of these phenomena were seen at least, the points of deteriorated parts were counted.
The points of existing parts and deteriorated parts in House A and B were shown in Table 3, whose columns of parts and members and materials indicated only the items that the tested house had.

Table 1. Results of general seismic diagnosis.

House	Direction	Story	P (kN)	E	$P \times E$	Q_d (kN)	Score
A	X	2	28.06	1.00	28.06	18.32	1.53
		1	59.06	1.00	59.06	39.99	1.48
	Y	2	17.96	1.00	17.96	18.32	0.98
		1	24.85	1.00	24.85	39.99	0.62
B	X	2	25.90	1.00	25.90	18.32	1.41
		1	60.77	1.00	60.77	39.99	1.52
	Y	2	17.96	1.00	17.96	18.32	0.98
		1	24.85	1.00	24.85	39.99	0.62

Table 2. Evaluation of the reduction factor of deterioration

Parts		Members and materials	House A		House B	
			D_e	D_d	D_e	D_d
Roof		Roof tile	2		2	
Gutter		Eaves and gooseneck	2		2	
		Downspout	2		2	
Exterior wall		Mortar	4	4	4	2
Balcony		Floor drain	1		1	
Interior wall	General room	Interior wall and lower part of the opening	2		2	
	Bathroom	Except for tiles	2		-	-
Floor	Surface	General room	2		2	2
		Corridor	1		1	1
	Floor bottom		2		2	
Total			20	4	18	5
Reduction factor of deterioration			0.80		0.72	

Note: Columns of parts and members and materials indicated only the items that the tested house had.

2) Precise seismic diagnosis 1 (Ultimate capacity method)
The score of general seismic diagnosis; I_{wp1} were defined by the equation (3).

$$I_{wp1} = Q_d / Q_r = \frac{(Q_{wn} + Q_{ww}) \cdot F_s \cdot F_e}{Z \cdot R_t \cdot A_i \cdot C_o \cdot \sum W_i} \quad (3)$$

where, Q_d: Ultimate capacity (kN),

Q_r: Required capacity (kN),
$Q_{wn} = \sum P_{wo} \times L \times min(C_f,\ C_{dw})$,
$Q_{ww} = \sum P_{wo} \times L \times k_0 \times min(C_f,\ C_{dw})$,
P_{wo}: Ultimate capacity of walls (kN/m),
L: Length of walls (m),
C_f: Reduction factor of joints,
C_{dw}: Reduction factor of deterioration,
K_0: Reduction factor of opening,
F_s: Reduction factor by stiffness ratio,
F_e: Reduction factor by eccentricity ratio and floor stiffness,
Z: A value specified by the Minister of Land, Infrastructure and Transport within a range of between 1.0 to 0.7 reflecting extent earthquake damage, seismic activity and other seismic characteristics based on the earthquakes record in the region,
R_t: A value representing vibration characteristics of building,
A_i: A value representing a vertical distribution of seismic story shear coefficient,
C_0: Standard shear coefficient,
and $\sum W_i$: Total weight of the story and upper story.

The score of general seismic diagnosis shows Table 3. The scores of 1st story in the main shaking direction of Y in Houses A and B were judged to have high possibility. House B would be decided to be seismic reinforced, because B showed slightly low value than A.

Table 3. Results of precise seismic diagnosis 1 (Ultimate capacity method)

House	Direction	Story	Q_r (kN)	Q_d (kN)	Q_d / Q_r	Judgment
A	X	2	20.96	25.83	1.23	Hope not to collapse
		1	43.44	51.00	1.17	Hope not to collapse
	Y	2	20.96	17.80	0.85	Possibility of collapse
		1	43.44	21.89	0.50	High possibility of collapse
B	X	2	20.96	26.32	1.26	Hope not to collapse
		1	43.44	55.13	1.27	Hope not to collapse
	Y	2	20.96	17.60	0.84	Possibility of collapse
		1	43.44	20.85	0.48	High possibility of collapse

3) Precise seismic diagnosis 2 (Response and limit capacity method)
Response and limit capacity method were conducted to the House A and B. The load-displacement relations were obtained by the contraction of the building to a single degree of freedom. The load-displacement curves were compared with the demand spectrum and amplified to just contact with the spectrum, as shown in Fig. 4. The reciprocal number of amplification rate, α at that time was defined as the score of precise seismic diagnosis 2 (Response and limit capacity method). The scores of the diagnosis were shown in Table 4.

Table 4. Results of precise seismic diagnosis 2 (Response and limit capacity method)

House	direction	
	X	Y
A	0.79	0.31
B	0.79	0.20

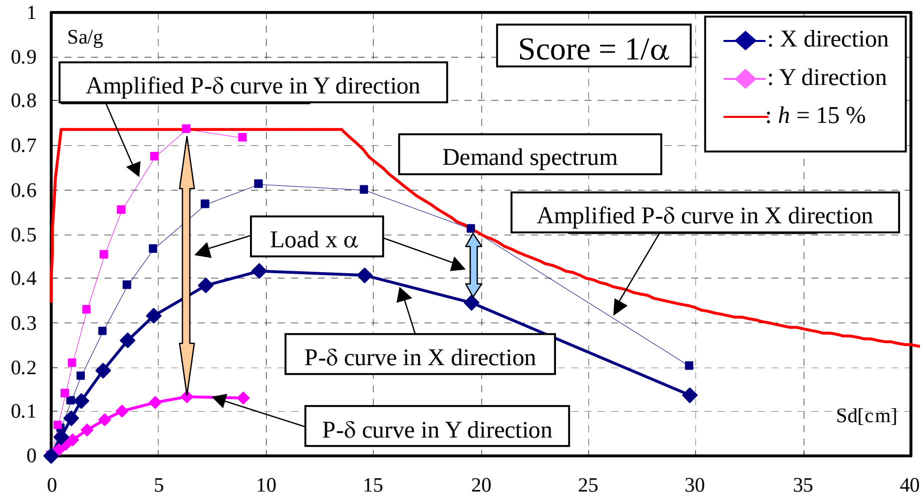


Fig. 4. Method of precise seismic diagnosis 2 (Response and limit capacity method)

As mentioned above, it was clarified that the evaluation of the seismic diagnosis were severe in order of precise 2 (Response and limit capacity), precise 1 (ultimate capacity), general diagnosis.

6. Seismic Reinforcement

Seismic reinforcement was designed based on the following concepts:

1) An evaluated score of 1.5 in the wood structure was to be aimed so that the house would not collapse even under the severe earthquake like the Hyogo-Nambu Earthquake, which exceeds the earthquake assumed in The Building Standard Law to rarely occur.
2) The seismic reinforcement design would be decided by the scores evaluated by the precise seismic diagnosis with the method of ultimate capacity, finally. The scores of the other seismic diagnosis would be used as references.
3) The floor plan would be unchanged as much as possible to keep comfort of living, etc.
4) No special materials and hardware would be used, but ordinary materials (*e.g.* braces and structural plywood) and connector that are easily available would be used.
5) To prevent decrease coefficient of the insufficient joints strength and unbalanced shear walls arrangement, the joints would be reinforced so as to match the strength of shear walls, and the shear walls would be arranged equally.
6) To prevent the fracture of joints before the shear wall's fracture and to avoid the use of extremely strong connector, the walls that exceed the upper limit of the standard strength (14 kN/m) in the literature wouldn't be installed.
7) Wall reinforcement that involves removal of exterior mortar would be avoided, but the interior walls would be reinforced.

The aging of the houses was also diagnosed. Deterioration by biological attacks (rotting and termite damage) was observed at some parts, but the degree of the deterioration was slight for houses of the age. Thus, the aging was decided to be not considered in the seismic diagnosis.

As a result of seismic diagnosis, it was clarified that the House B in the main vibration direction Y was short of the amount of shear wall in 1F and the joint strength of 2F, significantly. Based on the concepts mentioned above, the seismic reinforcement of House B aimed for a score of 1.5, as shown in Fig. 5.

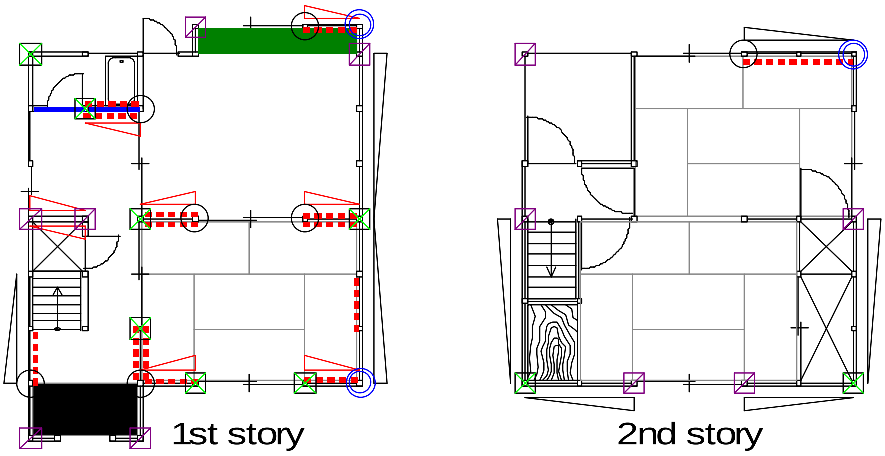


Fig. 5. Plan of House B after seismic reinforcement.

: Added brace (top grade in JAS of structural soft wood with cross section of 45 × 90 mm)
End joint: Box-shaped connector

: Added plywood (structural plywood of top grade in JAS with 9 mm thickness)

: Added beam with cross section of 100 × 150 mm (Western Hemlock)

: Reinforced diaphragm and hanging wall in the portion of set-back

: Hold down fastener for 25 kN

: Hold down fastener for 15 kN

: connector for 8.5 kN

: connector for 5.1 kN

The connector for through columns were installed only at the base on the 1st story and the top of the 2nd story.

In the seismic reinforcement, a beam was added to the portion where there was no beam and the shear wall need to be installed. On reinforcing the wall in the portion of set-back, the diaphragm and hanging wall were reinforced by plywood, so that the reinforcement of the wall would be effective.

7. Shaking Table Tests

6.1 Input seismic wave

The actual seismic waves recorded at JR Takatori Station under the Hyogo-Nambu Earthquake in 1995 were input in full scale. The maximum values of the wave are shown in Table 5. The waves were input so that the NS component acted along the Y-axis of the houses. The values in the table were separately corrected for their neutral axes to prevent integral displacement waveforms from diffusing, but the intensity of the waves is equivalent to the original records.

Table 5. Maximum values of the input seismic waves.

Direction	Acceleration (gal)	Velocity (kine)	Displacement (cm)
NS	641.7	149.2	86.33
EW	666.2	117.0	37.78
UD	289.5	16.50	11.15

7.2 Test results

The time historical waveforms of the relative story displacement of the houses on their first and second stories along the Y axis are shown in Fig. 6. The 1st story of House A recorded a relative story displacement of -383 mm but did not collapse. Subsequently, the house was displaced +657 mm toward the other direction on the 1st story and collapse (Photo. 7) before the displacement returned to the negative side. House B deformed to a relative story displacement of 180 mm on both sides and did not collapse. However, large cracks occurred on the exterior mortar wall on the first story, parts of which came off. Some of the structural plywood and braces added for reinforcement failed off, some joint connectors became loose, and some screws pulled out. In House A, which collapsed, many tenon joints were not broken but pulled out. After shaking, a precise seismic diagnosis of House B was conducted by considering the damages to the house. The score of the 1st story in the Y-direction was 0.86 (1.57 before shaking), so it was clarified that the seismic performance of House B was declined by the JR Takatori full scale shaking.

Photo. 7. Collapse behavior.

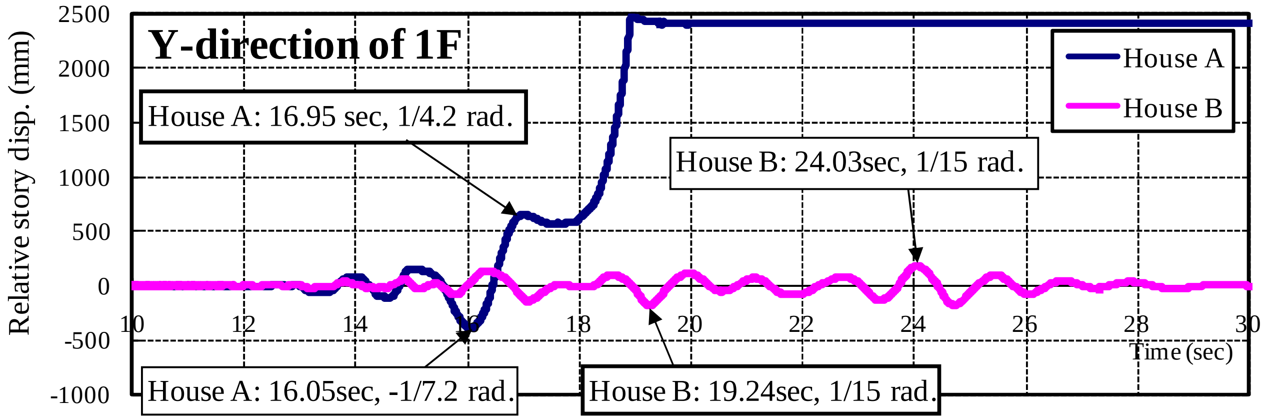


Fig. 6. Time history waveform of relative story displacement of Houses A and B in the Y direction.

7.3 Verification of the precise seismic diagnosis method 2 (Load-carrying capacity method)

The relationships between load and deformation were calculated by the precise seismic diagnosis method 2 based on Horizontal load-carrying capacities. A comparison between the calculated and monitored relationships is shown in Fig. 7. The dotted lines in the figure show the required ultimate strength calculated using the horizontal load-carrying capacity method. The calculated relationship between load and deformation using the precise seismic diagnosis method was far smaller than the required ultimate strength in House A, which collapsed. The all calculated values were smaller than the measured values, so the precise seismic diagnosis method 2 based on Horizontal load-carrying capacity was on safety side. The difference between the calculated and measured values was slightly larger in House A, which was not reinforced, than in House B, which was reinforced. Because the shear wall with plywood or brace, which was relatively new seismic elements and had datum enough to evaluate, could be evaluated exactly, but those with the mud wall and *Nuki*, which was relatively old seismic elements and didn't have enough datum, couldn't be evaluated. The experimental values at which the houses lost the restoration capacity were also larger than the calculated values in both houses.

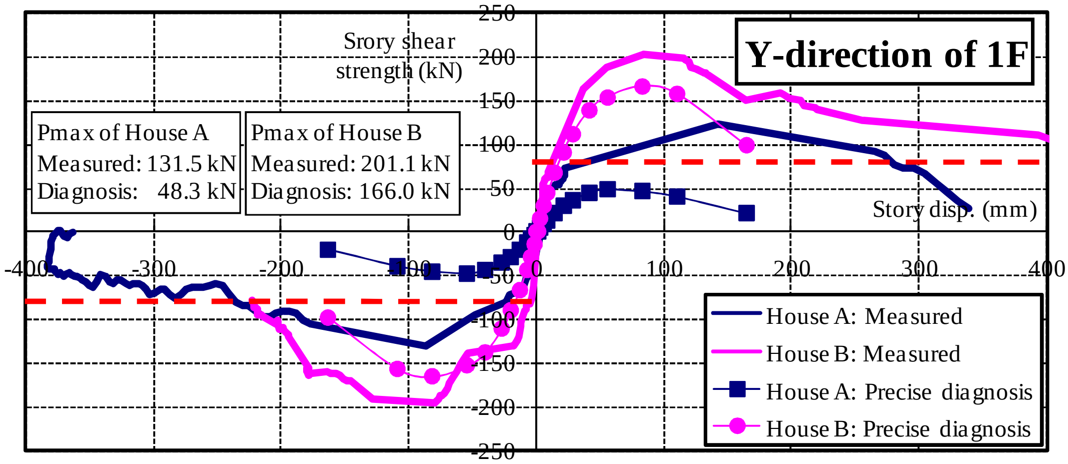


Fig. 7. Comparison between the results of the precise seismic diagnosis and the shaking table test.

8. Conclusions

Results of A shaking table test of two old houses and the verification of validity for the precise seismic diagnosis were summarized as follows:

1) The seismic reinforcement was confirmed to be effective, because House A with seismic diagnosis score of 0.43 collapsed, and House B, which was reinforced to score of 1.57, did not collapse. The possibility that houses with a score of at least 1.5 might resist a severe earthquake beyond the assumption in The Building Standard Law was suggested.
2) The both tested houses were stronger than the strength estimated by the precise seismic diagnosis with the horizontal load-carrying capacity method. The precise seismic diagnosis method could evaluate the houses on safety sides for both strength and ductility.

References

[1] "Methods of seismic diagnosis and reinforcement of wood houses", supervised by the Housing Bureau of MLIT, issued by the Japan Building Disaster Prevention Association, 2004.

[2] Takahiro TSUCHIMOTO, et. al., "Studies on Earthquake hazard mitigation of existing wood houses by Use of E-Defense. Part 1. Collapsing behavior of removed and reconstructed retrofit and non-retrofit houses". *The 12th Japan Earthquake Engineering Symposium*, Tokyo Institute of Technology, Tokyo, 2006, No.0245.