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DYNAMIC PERFORMANCE EVALUATION OF BRACED SHEAR WALL WITH NEW BRACE FASTENER FOR WOODEN HOUSES

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ABSTRACT: In Japanese Post and Beam construction wooden houses, diagonal wood brace is a typical shear wall. The end of a wood brace is fastened to a column and a lateral member, such as sill or beam, with a metal brace fastener. However, ductility and damping of the braced shear wall are relatively low compared to nailed plywood shear wall. From the reason, a new brace fastener was developed, which includes damping mechanism. In this study, seismic performance of the braced shear wall with the new brace fastener was examined by shake table test. From the test results, hysteresis model of the braced shear wall with the new brace fastener was developed, and earthquake response analysis of typical 1,320 two-storied wooden houses with the new brace fastener was conducted to build database of earthquake response displacement. Finally, an application of the new brace fastener to a real wooden house were performed and the maximum story displacement was evaluated.

KEYWORDS: Wooden house, Brace fastener, High damping rubber, Shake table test, Earthquake response analysis

1 INTRODUCTION

In Japanese Post and Beam construction wooden houses, diagonal wood brace is a typical shear wall. Even nailed plywood shear wall has been used widely nowadays, the diagonal wood brace still plays an important role. The end of a wood brace is fastened to a column and a lateral member, such as sill or beam, with a metal brace fastener. A new brace fastener, as shown in Figure 1, was developed, which includes damping mechanism [1]. Though ductility and damping of the conventional braced shear wall are relatively low compared to nailed plywood shear wall, the new brace fastener absorbs relative displacement between the end of a brace and a column due to plastic deformation of a part of the new brace fastener.

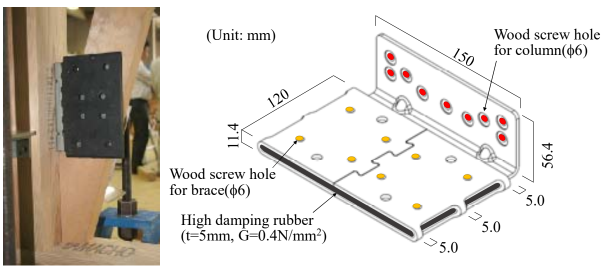

Figure 1: New developed brace fastener

2 SHAKE TABLE TEST

2.1 OUTLINE OF SHAKE TABLE TEST

Shake table test of the braced shear wall specimen with the new brace fasteners and conventional brace fasteners was conducted to evaluate the dynamic performance of them. The specimen was constructed by Japanese Post and Beam construction. Wall length of the specimen was 2,730 mm and it has four columns. Weight which was 15.8kN was loaded on the beam. Rollers were arranged along the longitudinal direction of the weight. Figure 2 shows the test apparatus and the specimen.

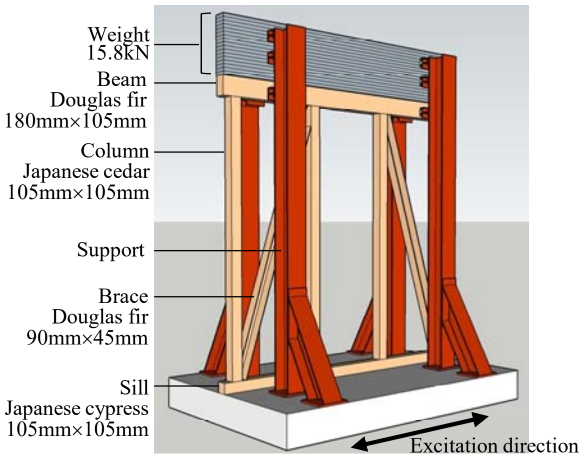

Figure 2: Test apparatus and specimen

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List of excitations is shown in Table 1. For the braced shear wall, three types of connection, namely the new developed brace fastener, conventional brace fastener and no metal fastener (one 150 mm-long nail only) were conducted, where configurations of wood braces were "X", "/ \" and "\ /". In addition to the braced shear walls, nailed plywood shear wall and nailed particle board shear wall were also conducted. Cases with both wood brace and nailed plywood were also performed.

JMA Kobe NS wave (observed at Kobe branch of Japan Meteorological Agency on January 17th in 1995) and Mashiki EW waves (observed at KiK-net Mashiki in Kumamoto pref. on April 14th(1st) and 16th(2nd) in 2016) as shown in Figure 3 were input to the specimen in one direction. For each shear wall, input level of the waves was increased step by step. Before the earthquake input, small pulse waves were input to obtain the natural frequency of the specimen.

Acceleration pickups were placed on the beam, the sill and the shake table, and lateral displacements of the beam and the sill were measured by displacement meters. Vertical displacements of the columns and relative displacements between the end of a wood brace and a sill or a beam were also measured.

Table 1: *List of excitations*

Shear wall	Brace config.	Spec	Wave	Input level
Brace	X	Conventional	Kobe	20% - 100%
Brace	X	Nail (N150)	Kobe	20% - 60%
Plywood		N50@150	Kobe	20% - 60%
Particle board		N50@100	Kobe	20% - 80%
Brace	X	New fastener	Kobe	20% - 100%
Brace	X	New fastener	Kobe	20% - 100%
Brace	/ \	New fastener	Kobe	20% - 100%, 80%, 100%x3
Brace+Plywood	X	Conventional N50@150	Kobe	20% - 80%, 100%x5
Brace+Plywood	X	New fastener N50@150	Kobe	20% - 60%, 100%x5
Brace(clearance)	\ /	New fastener	Kobe	20% - 60%, 80%x4
Brace	X	Conventional	Mashiki 1st and 2nd	50%, 70%
Brace	X	New fastener	Mashiki 1st and 2nd	50%, 70%x3
Brace	\ /	New fastener	Mashiki 1st and 2nd	50%, 70%x3, 100%

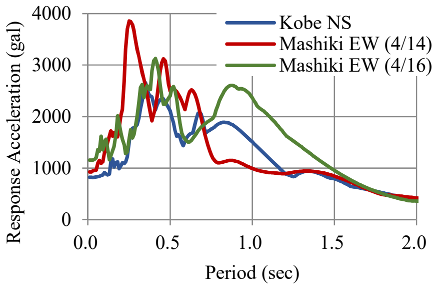


Figure 3: *Response acceleration spectra*

2.2 RESULT OF SHAKE TABLE TEST

2.2.1 Natural frequency

Natural frequencies of each shear wall are shown as Figure 4 which were calculated from the response displacement under the pulse wave. Natural frequency of the braced shear wall with the new fasteners was 3.1 Hz, while the one with conventional fasteners was 2.8 Hz. Considering the values, it is found that the shear stiffness of the braced shear wall with the new fasteners is 20% higher than the one with conventional fasteners. Moreover, it is also found that even the end of a wood brace is fastened with one nail, the initial stiffness of the shear wall is almost same level as the one with a conventional fastener. Therefore, it is considered that the initial stiffness of a braced shear wall is greatly affected by the compressive brace.

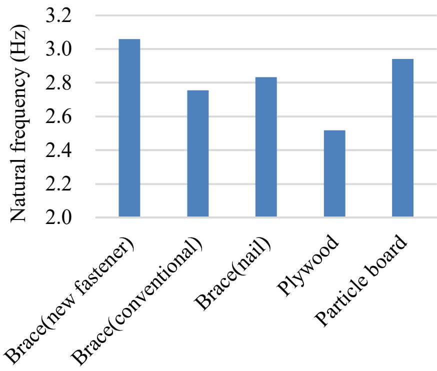


Figure 4: *Natural frequency of shear walls*

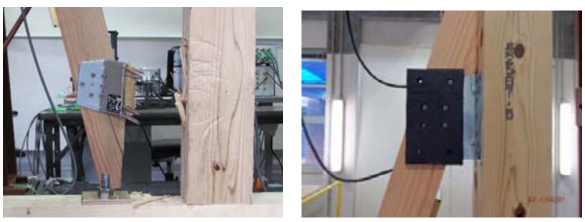
2.2.2 Failure mode

Figure 5 shows the nailed plywood shear wall and the braced shear wall whose end of a wood brace was nailed after the JMA Kobe 60% input. The nails on the plywood and the nail at the end of a wood brace were pulled out and the shear stiffness dropped down. Pull-out of nail on the particle board occurred on JMA Kobe 80% input.

Figure 6 shows the end of a wood brace with a conventional brace fastener and the new brace fastener after JMA Kobe 100% input. For the braced shear wall with conventional brace fasteners, buckling of a wood brace occurred and wood screws on the column were pulled out. On the other hand, the braced shear wall with the new fastener showed no damage.

(a) Nailed plywood *(b) Brace with nail*

Figure 5: *After JMA Kobe 60% input*



(a) Conventional fastener *(b) New fastener*

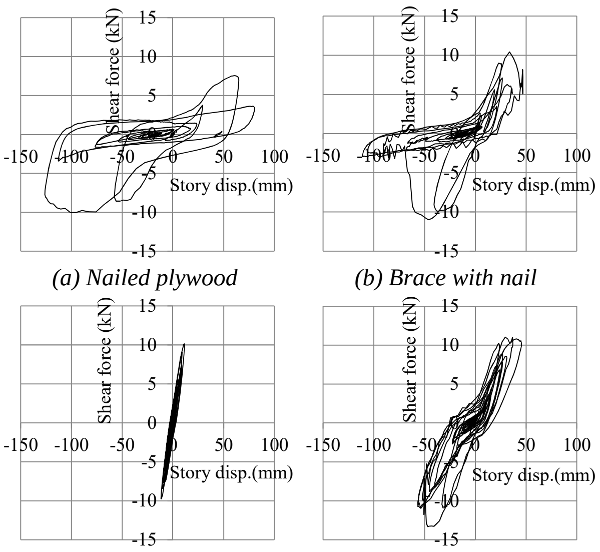
Figure 6: *After JMA Kobe 100% input*

2.2.3 Shear force-story displacement relationship

Figure 7 shows relationships between shear force and story displacement under JMA Kobe 60% input. Shear forces of the nailed plywood shear wall and the braced shear wall only with nail were dropped sharply. The maximum story displacement of the braced shear wall with the new brace fasteners was approximately 10 mm while the one with conventional brace fasteners was about 50 mm under 60% of JMA Kobe input. Moreover, though the story displacement of the one with the new fasteners was smaller than the one with conventional fasteners, the maximum shear forces of the two braced shear walls were almost the same. From the result, it is considered that the damping mechanism of the new brace fastener worked efficiently.

Figure 8 shows shear force-story displacement relationships under 100% of JMA Kobe input. The shear stiffness of the braced wall with the new brace fasteners did not decrease, while the shear force of the one with conventional brace fasteners dropped significantly and the wall collapsed.

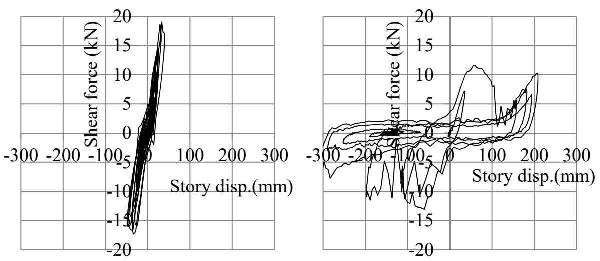
Figure 9 shows shear force-story displacement relationships under 70% of Mashiki input. The maximum story displacement of the braced shear wall with the new fastener was approximately 60% of the one with a conventional fastener.



(a) Nailed plywood (b) Brace with nail

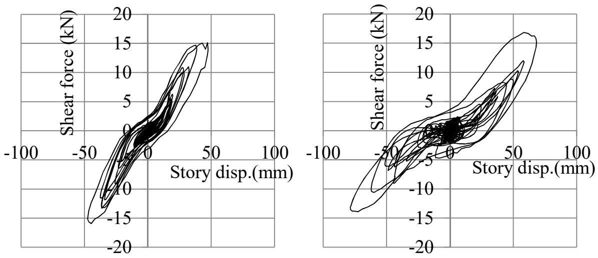
(a) New fastener (b) Conventional fastener

Figure 7: *Shear force-story displacement relationship under JMA Kobe 60% input*



(a) New fastener (b) Conventional fastener

Figure 8: *Shear force-story displacement relationship under JMA Kobe 100% input*



(a) New fastener (b) Conventional fastener

Figure 9: *Shear force-story displacement relationship under Mashiki 70% input*

2.2.4 Maximum story displacement

Figure 10 shows maximum story displacements of the shear walls under JMA Kobe input.

On 40% of JMA Kobe input, the maximum story displacement of the braced shear wall with a conventional fastener was approximately 20 mm, while the maximum story displacement of the braced shear wall with the new fastener was about 5 mm and the one of the nailed particle board shear wall was the same level. The maximum story displacements of the nailed plywood shear wall and the braced shear wall only with nail were over 100 mm under 60% of JMA Kobe input, while the one of the braced shear wall with a conventional brace fastener was approximately 50 mm. For the braced shear wall with the new brace fastener and the nailed particle board shear wall, the maximum story displacement was about 10 mm.

Though maximum story displacement of the braced wall with conventional brace fasteners was over 300 mm, the one with the new brace fasteners was approximately 50 mm under 100% of JAM Kobe input. After following three 100% of JMA Kobe waves were input to the braced shear wall with the new fastener, though the maximum displacement increased to 150 mm due to buckling of compressive brace, no damage on the new fastener was observed.

Figure 11 shows maximum story displacements of the shear walls under Mashiki input. It is found that the maximum story displacement of the braced shear wall with the new fastener is approximately 60% of the one with a conventional fastener under the series of the input.

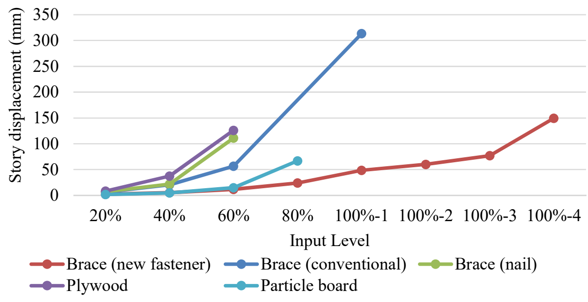


Figure 10: *Maximum displacement under JMA Kobe input*

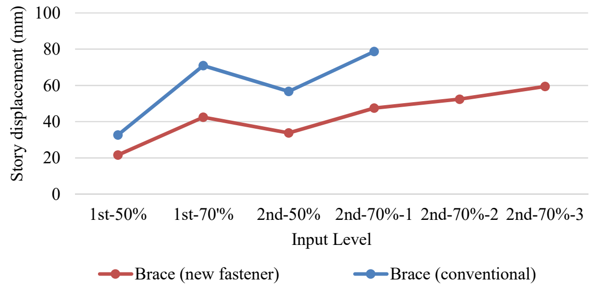


Figure 11: *Maximum displacement under Mashiki input*

2.2.5 Maximum response acceleration

Figure 12 shows maximum response acceleration of the shear walls under JAM Kobe input.

On 60% of JMA Kobe wave, the response acceleration of the braced shear wall with conventional fasteners was the maximum, 816 gal, while the one with the new fastener was 622 gal which is 76% of a conventional fastener. The response acceleration of the other shear wall was the same level as the braced shear wall with the new fastener.

On 80% of JMA Kobe wave, the response acceleration of the braced shear wall with the new fastener is larger than the one of the nailed particle board shear wall by 20%. However, the maximum story displacement of the braced shear wall with the new fastener is about half of the nailed particle board shear wall.

The response acceleration of the braced shear wall with a conventional fastener does not exceed approximately 800 gal under over 60% of JMA Kobe input, because its natural period became larger due to damage. For the braced shear wall with the new fastener, the response acceleration was relatively stable even under repeated 100% of JMA Kobe input while the story displacement was also relatively stable.

Figure 13 shows maximum response acceleration under Mashiki input. The response acceleration of the braced shear wall with the new brace fasteners was stable under consecutive six Mashiki wave input. For the braced shear wall with conventional fasteners, though the maximum response acceleration was almost the same as the one with the new fastener, the shear stiffness decreased and the story displacement increased through the four consecutive inputs.

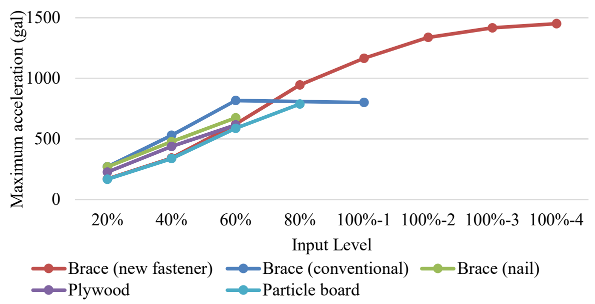


Figure 12: *Maximum response acceleration under JMA Kobe input*

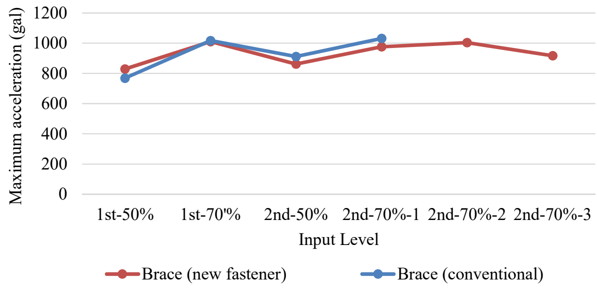


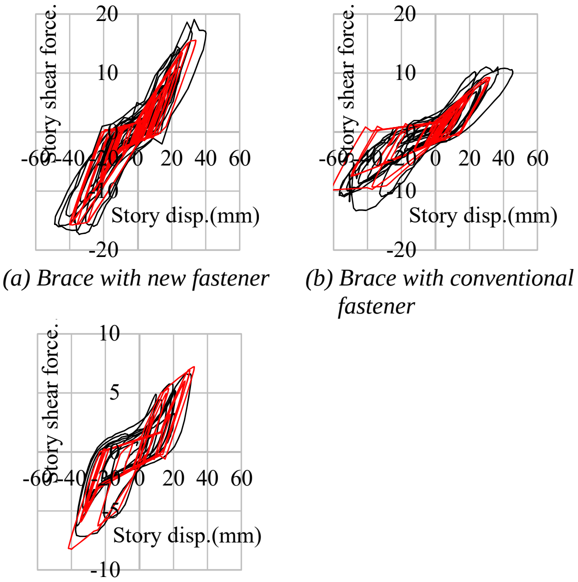
Figure 13: *Maximum response acceleration under Mashiki input*

3 EARTHQUAKE RESPONSE ANALYSIS OF TYPICAL WOODEN HOUSES

3.1 ANALYSIS MODEL

Earthquake response analysis of typical two-storied wooden houses which have braced shear walls with the new brace fasteners and conventional brace fasteners was performed.

As shear force-story displacement relationship model, Wayne-Stewart model was adopted. The parameters of the Wayne-Stewart model were adjusted considering the time history of the story displacement on shake table test. Figure 14 shows the shear force-story displacement models of the braced shear wall with the new fasteners, the one with conventional fasteners and the nailed plywood shear wall for earthquake response analysis.



(a) Brace with new fastener *(b) Brace with conventional fastener*

(c) Nailed plywood

Figure 14: *Hysteresis models of shear walls (black line: shake table test, red line: model)*

Parameters of the earthquake response analysis were ratio of existing wall length to required wall length on the first floor (Re_1, from 1.0 to 2.0), ratio of Re_2 (ratio of existing wall length to required wall length on the second floor) to Re_1 (from 1.0 to 2.0), ratio of the second floor area to the first floor area (Rf, from 0.7 to 1.0) and ratio of wall length of nailed plywood shear walls to whole wall length (Rp, from 0 to 0.8). Re_1 and Re_2 are defined as $3.57n/0.2w$ (n: number of brace, w: weight of the building(kN)). Number of analysis model was 1,320. Input earthquake wave to the analysis models was BCJ L2 (Level 2 simulated earthquake wave for structural design by The Building Center of Japan) wave as shown in Figure 15. As for damping ratio, 5% was applied to all analysis models.

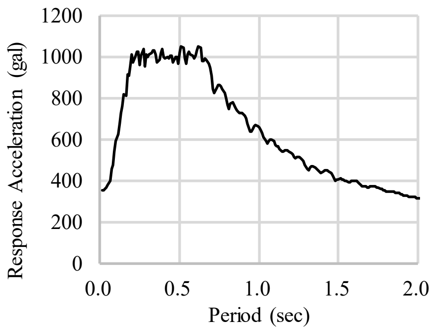


Figure 15: *Response acceleration spectra of BCJ L2 wave (h=5%)*

3.2 RESULT OF ANALYSIS

Figure 16 shows relationship between maximum story displacement and Re_1. It is found that the story displacement decreases as the Re_1 increases. And the maximum story displacement is approximately less than 90 mm when the Re_1 is more than 1.5.

Among four parameters, Re_1, Re_2/Re_1, *Rf* and *Rp*, it was found that Re_1 and Re_2/Re_1 affect the story displacement largely by analysing variation of the story displacement. Therefore, contour map of the story displacement when the new brace fasteners are installed was shown in Figure 17, in which horizontal axis and vertical axis are Re_1 and Re_2/Re_1, respectively. The story displacement, when Re_2/Re_1 is 1.2 or over, is from 110 mm to 145 mm on Re_1=1.0, from 64 mm to 69 mm on Re_1=1.5 and from 33 mm to 34 mm on Re_1=2.0. On the case of Re_2/Re_1=1.0, because shear wall on the second floor reaches yield strength before the shear wall on the first floor reaches, there is a tendency that the story displacement on the second floor is larger than the one on the first floor.

For the story displacement on the second floor, it is from 14 mm to 38mm on Re_1=1.0, from 13 mm to 24 mm on Re_1=1.5 and from 9 mm to 18 mm on Re_1=2.0 when Re_2/Re_1 is 1.2 or over. On Re_2/Re_1=1.0, the story displacement on the second floor is larger than the one of the first floor due to the above reason.

In the case of analysis with a conventional brace fastener, the contour map is shown as Figure 18. The story displacement, when Re_2/Re_1 is 1.2 or over, is from 161 mm to 171 mm on Re_1=1.0, from 84 mm to 87 mm on Re_1=1.5 and from 62 mm to 65 mm on Re_1=2.0, which is from 1.2 to 1.9 times of the ones with the new brace fastener.

For the second floor, it is from 14 mm to 37 mm on Re_1=1.0, from 15 mm to 28 mm on Re_1=1.5 and from 13 mm to 22 mm on Re_1=2.0, which is 1.4 times as much as the one with the new fastener at a maximum.

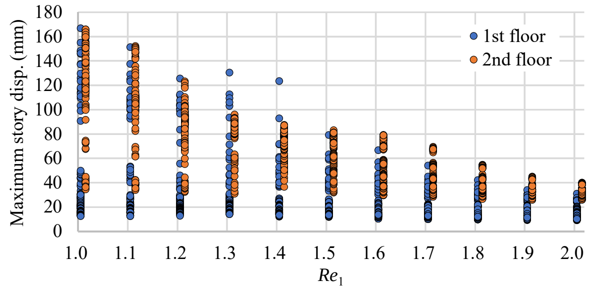


Figure 16: *Maximum story displacement*

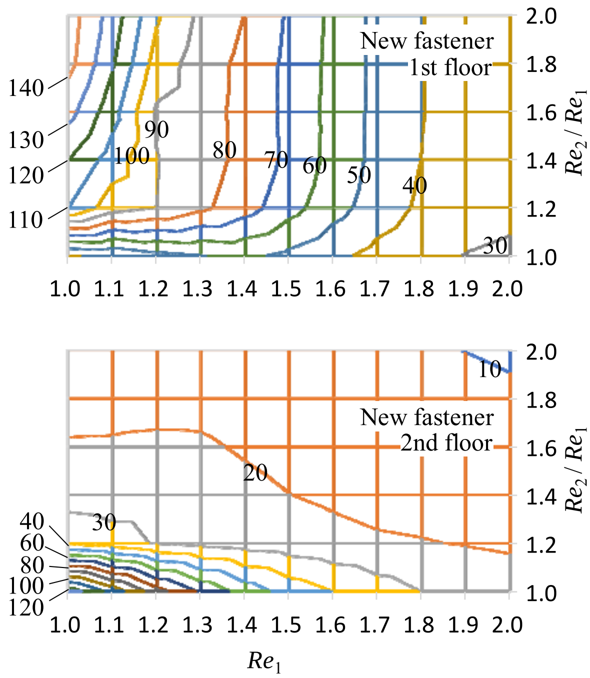


Figure 17: *Maximum story displacement of braced shear wall with new fastener (unit: mm)*

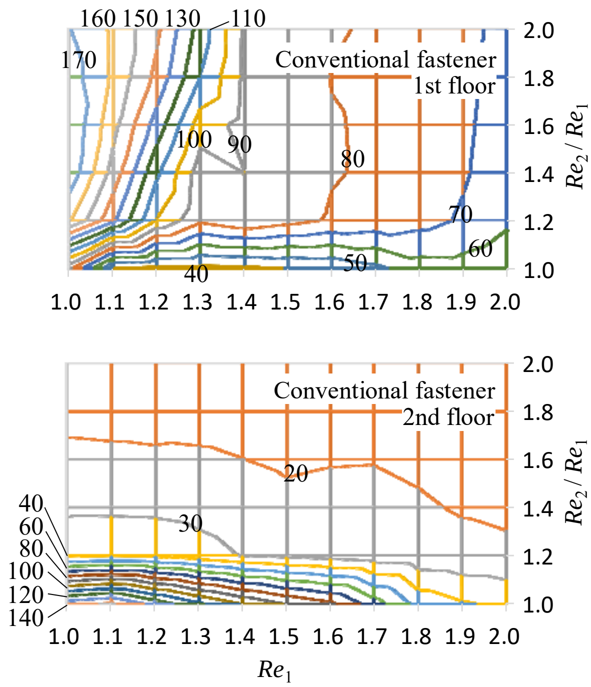


Figure 18: *Maximum story displacement of braced shear wall with conventional fastener (unit: mm)*

4 APPLICATION FOR TWO STORIED EXISTING WOODEN HOUSE

The object building was built in 1988, whose floor area of the first floor and the one of the second floor were 85.29m^2 and 33.95m^2, respectively. According to seismic diagnosis, the seismic index of the building was below 1.0, which means "there is strong possibility of collapse under large earthquake" as shown in Table 2.

Considering the result of the seismic diagnosis, heavy roof tiles were replaced with lightweight roof tiles and wood braces with the sixteen new brace fasteners were installed in the first floor. The seismic index after the seismic rehabilitation increased to the value above 1.0 as shown in Table 3, which means "there is no possibility of collapse."

Furthermore, maximum story displacement of the building under large earthquake was evaluated. The maximum story displacements on the first floor are listed in Table 4, where it is found that the ones reduces to approximately 45% of the ones before the seismic rehabilitation including installation of the new brace fasteners.

Table 2: *Result of seismic diagnosis*

Direction	Floor	Required shear strength Qr (kN)	Shear strength Q (kN)	Q/Qr	Judgment
X	2nd	23.49	8.32	0.35	Strong possibility of collapse
	1st	65.72	10.94	0.17	Strong possibility of collapse
Y	2nd	23.49	10.21	0.43	Strong possibility of collapse
	1st	65.72	45.96	0.70	Strong possibility of collapse

Table 3: *Result of seismic diagnosis after rehabilitation*

Direction	Floor	Required shear strength Qr (kN)	Shear strength Q (kN)	Q/Qr	Judgment
X	2nd	12.01	29.29	2.44	No collapse
	1st	56.63	87.47	1.54	No collapse
Y	2nd	12.01	32.76	2.73	No collapse
	1st	56.63	64.41	1.14	May not collapse

Table 4: *Maximum story displacement*

	Direction	Number of brace fastener		Story displacement (mm)
		New fastener	Conventional fastener	
Before seismic rehabilitation	X	0	16	133.8
	Y	0	14	157.4
After seismic rehabilitation	X	8	11	57.8
	Y	0	14	75.3

5 CONCLUSIONS

Seismic performance of the braced shear wall with the new brace fastener was examined by shake table test. Using the test results, earthquake response analysis was conducted to build database of earthquake response displacement of two-storied wooden houses. Finally, seismic performance of an existing wooden house with the new brace fastener was evaluated using the database.

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