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STRUCTURAL PERFORMANCE EVALUATION OF NEW BRACE FASTENER WITH DAMPING MECHANISM FOR WOODEN HOUSES

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ABSTRACT: To improve ductility and damping performance of braced wall in Post and Beam construction wooden house, a new brace fastener which fastens the end of a diagonal wood brace to the end of column was developed. The new faster is able to absorb relative displacement between the end of a brace and a wood frame. Moreover, due to the effect of plastic deformation of steel "bridge" and shear deformation of high damping rubber, stiffness and damping force are added to the fastener. In this paper, static shear loading test of a wood frame with a wood brace which is fastened by the new brace fasteners, incremental analysis and earthquake response analysis of two-storied wooden houses with the new brace fasters are presented. It was found that the new brace faster reduces story drift of wooden houses to less than 50% under large earthquake motion compared to conventional fastener.

KEYWORDS: Brace Fastener, Response Control, High Damping Rubber

1 INTRODUCTION

In Japanese Post and Beam construction wooden houses, diagonal wood brace is one of the most useful and important seismic member. However, its ductility is not good in comparison with nailed plywood wall. Its connection between the end of a diagonal wood brace and the corner of column and sill or beam is not able to absorb the vibration energy under earthquakes efficiently. To improve the ductility and damping performance, a new brace fastener which fastens the end of a diagonal wood brace to the end of column was developed for Post and Beam construction wooden houses.

The new brace fastener has steel "bridge" which deforms and absorbs relative displacement between the end of a brace and a wood frame when a brace is subjected to a tensile load. Moreover, under a repeated load, the "bridge" absorbs vibration energy due to plastic deformation of steel. In addition to the "bridge", a high damping rubber which is included in the brace fastener is subjected to shear force under a tensile repeated load, stiffness and damping force are added to the fastener. The new brace faster contains not only stiffness but also ductility and damping, it contributes response control effect to a brace fastener.

In this paper, shear loading test of a wood frame with a wood brace which is fastened by the new brace fastener and earthquake response analysis of two-storied wooden houses which have wood braces with the new brace fasters and conventional brace fasters are presented.

Response control devices for wooden houses on the market nowadays are relatively high price. The manufacturing cost of this new brace faster is lower in comparison with the devices on the market. It is expected that a large number of wooden houses are equipped with this new fastener and response control will be standard function for wooden houses. This new brace fastener contributes to relieve society of fear of earthquakes.

2 OUTLINE OF THE NEW BRACE FASTENER

The schematic of the new brace fastener is shown in Figure 1. It is manufactured from a steel plate with 3.2mm thick as shown in Figure 2. Four portions are cut off to form six "bridges." Width of the bridge is 5mm each. To form the fastener, the plate is turned down at the bridges as shown in Figure 3 and a space of 120mmx 150mmx5mm between the plate is made. The both sides of the edge of the plate are jointed at the center of the fastener as shown in Picture 1. High damping rubber whose shear stiffness is 0.4N/mm^2 is inserted in the space with 5mm thick and glued to the inside faces of the plate. Covering rubber with 0.3-0.7mm thick is also glued to the outer face of the fastener at the same time. The covering rubber protects the steel from rust and average the shear force that affects the bridges. Picture 2 shows completed new brace fastener.

The brace fastener is fastened to a wood brace and a wood frame as shown in Picture 3 using six 45mm long wood screws and nine 75mm long wood screws respectively. Diameters of the 45mm long and 75mm long wood screws are both 3.7mm.

When a wood brace is subjected to a tensile force, relative displacement between two parallel faces of the

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plate is induced and strain is concentrated on the bridges. The bridges are plastic deformed and the high damping rubber is shear deformed. The two mechanisms absorb relative displacement between the end of a wood brace and the end of a column, and moreover, produce stiffness and damping force.

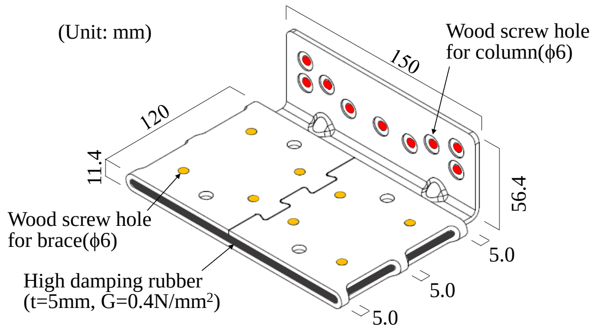


Figure 1: *New brace fastener*

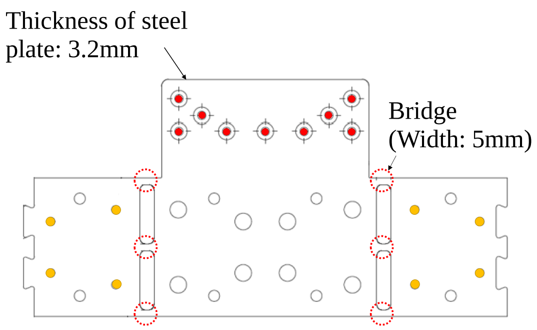


Figure 2: *New brace fastener before turning down*

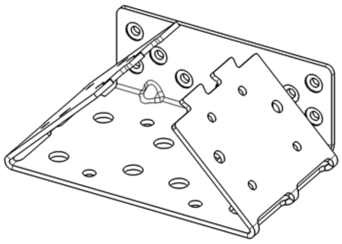
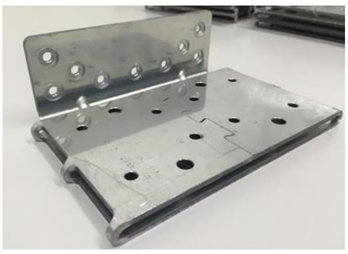


Figure 3: *Turning down to form the fastener*



Picture 1: *New brace faster before gluing high damping rubber*

Picture 2: *Completed new brace fastener*

Picture 3: *New brace fastener installed at the end of brace*

3 STATIC SHEAR LOADING TEST

Firstly, static shear loading test of a wood frame with a wood brace which is fastened by the new developed brace fasteners was conducted.

The specimen was constructed by Japanese Post and Beam construction system as shown in Figure 4. The wood frame consists of two columns, a sill and a beam. Species of the column and sill was Japanese cedar while the one of the beam was Douglas fir. Cross section of the column and the sill was 105mmx105mm while the one of the beam was 180mmx105mm. Each member is connected with tenon and mortice, and two 75mm long nails were driven penetrating tenon and mortice. A stud between two columns is connected to the beam and the sill with two 75mm long nails. A diagonal wood brace whose species was Tsuga heterophylla and the cross section was 90mmx45mm was installed inside the wood frame. The wood brace was fastened to the end of columns by the new brace fasteners. According to the Building Standard Law in Japan, allowable shear strength of a wood frame with single wood brace is prescribed as 3.57kN.

The specimen was set in the test apparatus, and tie rods were applied to restrict uplift of the beam. Lateral repeated load, from 0.17% (1/600) to 2% (1/50) of story drift, was applied to the beam and one directional load up to 6.67% (1/15) followed. Number of plus and minus repeated load was three on one stage of story drift. For compressive side of the wood brace, maximum story drift was up to 0.83% (1/120).

Three specimens with a brace were prepared for this test and one frame specimen without brace was also prepared and tested.

Figure 5 shows shear force-story drift relationships of the specimens. For this shear loading test, the high damping rubber which was installed of the brace fastener was not glued to the inside face of the fastener for conservative evaluation while the covering rubber was glued to the outer face of the fastener.

When the story drift exceeded 1% of story drift, relative displacement between the two parallel plates of the fastener was detected, area of the hysteresis loop became larger. Finally, the bridges between the two parallel plates of the fastener were torn off as shown in Picture 4. Though the test was continued until 6.67% (1/15) of story drift, remarkable decline of the shear force was not detected. In ultimate state, the head of a wood screw on the edge of the fastener was torn off in some specimen, it did not affect shear force. Split on the end of a wood brace was also observed as shown in Picture 5, however, decline of shear force was not detected.

Tests with the fastener whose high damping rubber was glued to the inside face of the plate were also conducted. Figure 6 shows skeleton curves of all the specimens. From the figure, the shear force of the specimen with glued high damping rubber is higher than the one without gluing from 1% of story drift. Considering the failure mode of the former test, yield of the bridge occurred at around 1% of story drift, therefore, the high damping rubber began to carry the shear force at around 1% of story drift. After that, shear force of the specimen with glued high damping rubber increased as the story drift increased smoothly. Moreover, variations in the shear forces of the specimens with glued high damping rubber was remarkably small, it is considered that the high damping rubber averages the shear force which affects six bridges.

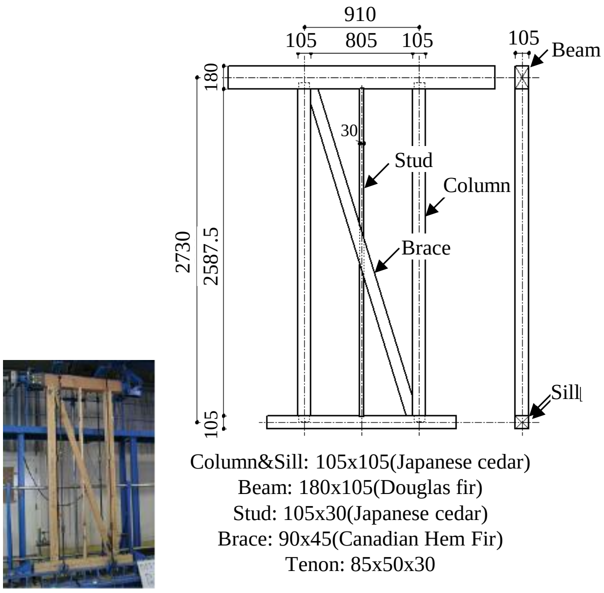
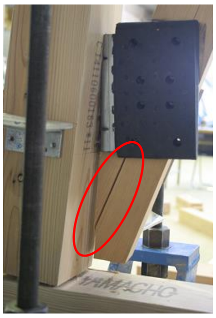


Figure 4: *Frame with single brace specimen*

Picture 4: *Tear of a bridge*



Picture 5: *Sprit on the end of brace*

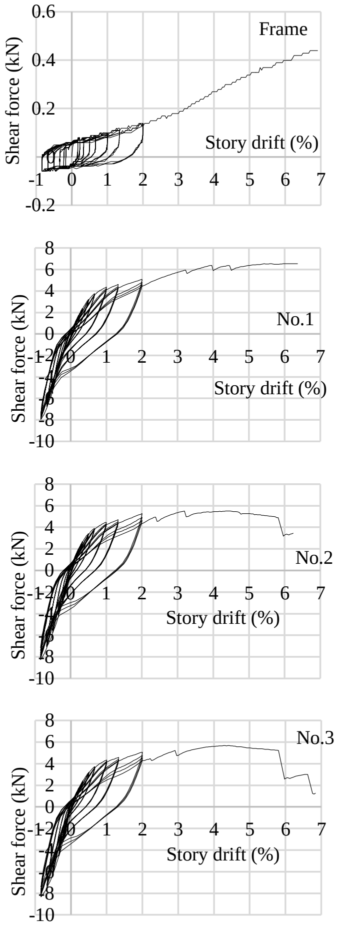


Figure 5: *Shear force-story drift relationship of braced specimen with the new brace fasteners*

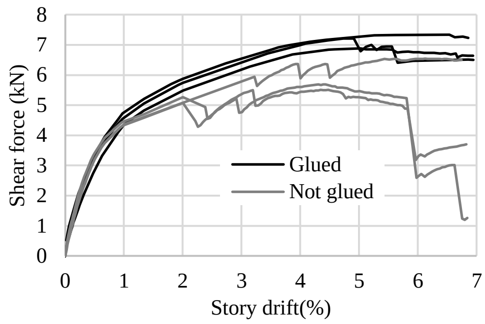


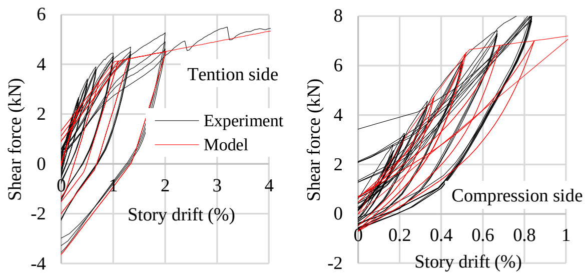
Figure 6: *Comparison between shear force-story drift relationship of specimen with glued and not glued high damping rubber*

4 INCREMENTAL ANALYSIS

Based on the static shear loading test, FEM analysis model was built. For the positive loading side, the brace is subjected to tensile force, tri-liner model as shown in Figure 7(a) was built while NCL model [1] was adopted for the negative loading side where the brace is subjected to compressive force as shown in Figure 7(b). For the compression side, it was assumed that buckling of a brace occurs at 6.5kN based on the former study.

FEM analysis model with double wood braces as shown in Figure 8 was built and incremental analysis was performed. Figure 9 shows shear force-story drift relationship from the analysis. Calculating equivalent viscus damping factor from the shear force-displacement relationship, 8.7% in 1.0% of story drift and 16.3% in 2% of story drift were derived as shown in Table 1. The value is approximately equal level as a wood frame with nailed plywood.

The analysis with conventional brace fasteners was also conducted. The analysis model which was calibrated by the shake table test results is shown in Figure 10 [2] and equivalent viscus damping factor was calculated. It is found that there is remarkable difference between the new brace fastener and conventional fastener in damping performance.



(a) Tension side (b) Compression side

Figure 7: *Hysteresis model of braced frame with the new fastener*

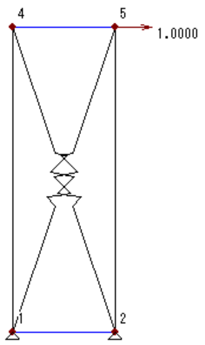


Figure 8: *Analysis model of frame with double brace for incremental analysis*

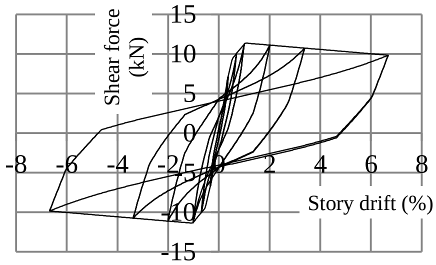


Figure 9: *Shear force-story drift relationship of braced frame with the new fastener from incremental analysis*

Table 1: *Equivalent viscus damping factor of braced frame with the new fastener and conventional fastener*

Story drift (%)	New fastener (%)	Conventional fastener (%)
0.33	4.4	4.9
0.67	8.6	5.1
1.00	8.7	5.2
2.00	16.3	5.1
3.33	19.8	5.1
6.67	23.0	5.1

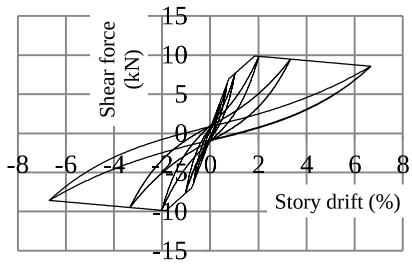


Figure 10: *Shear force-story drift relationship of braced frame with conventional fastener from incremental analysis*

5 EARTHQUAKE RESPONSE ANALYSIS

Earthquake response analysis of the two-storied wooden house which has wood braces fastened by the new fasteners and conventional fasteners was performed.

Figure 11 shows analysis model of a two-storied wooden house. The non-linear diagonal springs in the model represent double wood brace and nailed plywood. Figure 9, Figure 10 and Figure 12 are hysteresis models of a wood frame with double wood brace fastened by the new brace fasteners, the one with double wood brace fastened by conventional brace fasteners and the one with nailed plywood respectively.

Parameters of the analysis model were a ratio of existing wall length to required wall length(R_e), a ratio of the second floor area to the first floor area(R_f) and a ratio of wall length of nailed plywood shear wall to whole wall length.

A double wood brace was arranged on the first floor and lumped masses at every node and wall length on the second floor were adjusted to meet the corresponding R_e and R_f.

Weight of the first floor(W_1) and the one of the second floor(W_2) of analysis models were calculated by Equation (1), (2) and (3).

$$W = 0.667 \cdot Q_a / C_0 / R_e \quad (1)$$
$$W_1 = W / (1+R_m \cdot R_f) \quad (2)$$
$$W_2 = W - W_1 \quad (3)$$

where W is weight of whole analysis model of a two-storied wooden house(= W_1+W_2). It is assumed that 33% of shear force which affects a wooden house is carried by non-structural members, so 0.667 is multiplied in Equation (1). Q_a is an allowable shear strength of a double wood brace on the first floor(=7.13kN), C_0 is ratio of required shear force to the weight of a building at damage limit (=0.2), R_m is ratio of weight of unit area on the second floor to the one on the first floor(defined as 0.7 in this study). In Building Standard Law in Japan, Q_a of shear walls and C_0 for wooden houses are defined as above. Natural period of the analysis model of R_f=1.0 in the case of R_e=1.0 and is 0.43 sec, the one of R_e=2.0 is 0.30sec.

Input earthquake waves to the analysis models were JMA Kobe which was scaled down to 55% and BCJ L2(Level 2 simulated earthquake wave for structural design by The Building Center of Japan). Figure 13 shows the response spectra of the two earthquake waves. Damping ratio of 5% was given to the all analysis models.

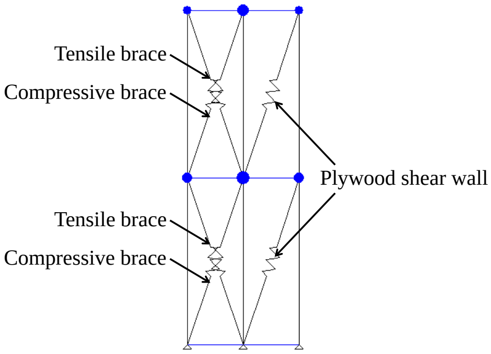


Figure 11: *Earthquake response analysis model*

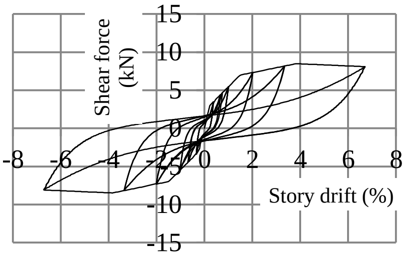


Figure 12: *Hysteresis models of frame with nailed plywood*

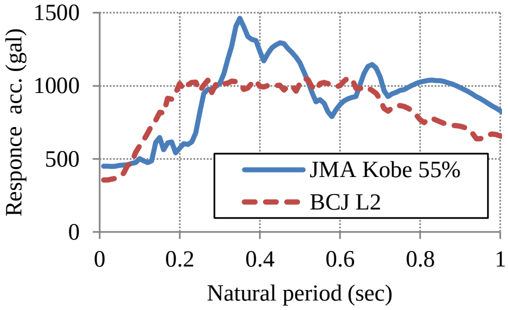


Figure 13: *Response spectra (h=5%)*

Figure 14 shows maximum story drift and story shear coefficient under JMA Kobe wave. The story drift tends to decreases as R_e increases. It is also found that maximum response drifts of the cases with the new brace fastener are conservative in comparison with the ones fastened by conventional fastener. At R_e=1.0, while drift of 1st floor with conventional fastener is over 5%, the one with the new fastener is approximately 3%.

As for story shear coefficient, it increases as R_e increases. The one with new fastener is slightly larger than the one with conventional fastener.

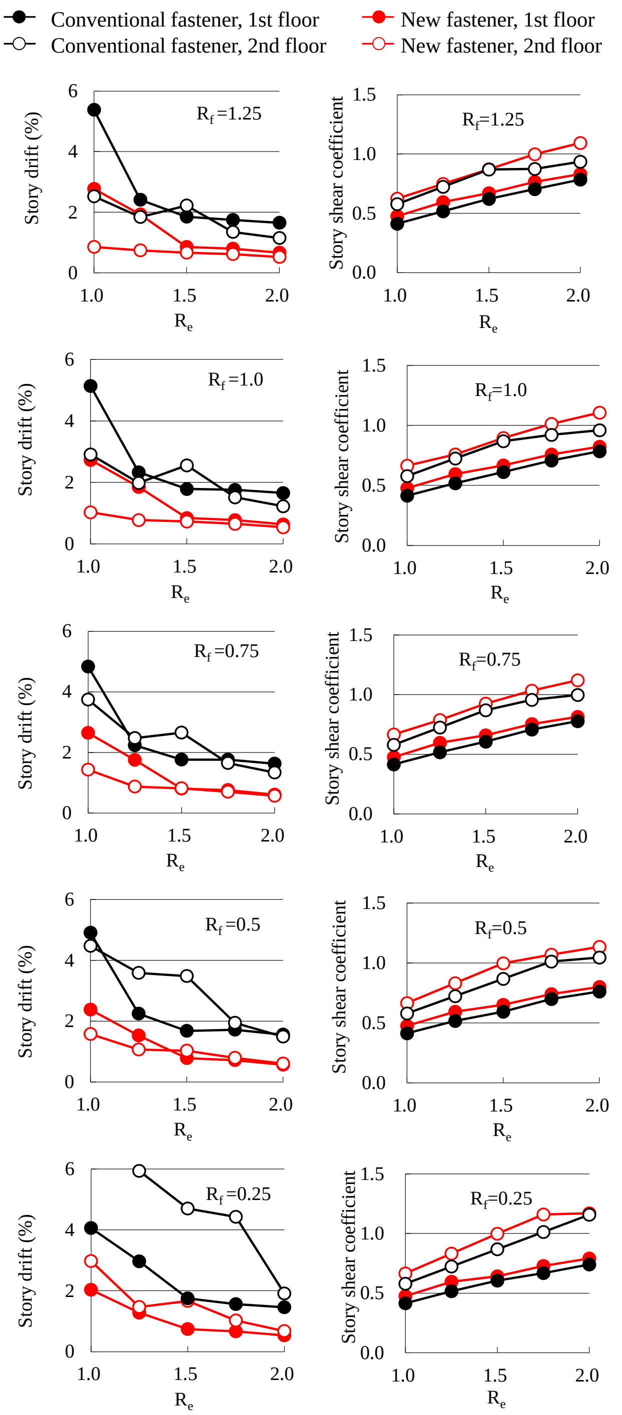
Figure 15(a) shows ratio of story drift with the new fastener to the one with conventional fastener, while Figure 15(b) shows the case of shear coefficient. The maximum ratio of story shear coefficient is 1.15 which is same value as ratio of maximum shear force of Figure 9 to the one of Figure 10. In most of the analysis cases on Figure 15 (a), the ratio of story drift is under 0.5. Considering the ratio of story shear coefficient is under 1.15, damping effect of the new fastener is remarkable.

Figure 16 and Figure 17 show earthquake response and coefficient of story drift and story shear coefficient under BCJ L2 wave. The response story drift with the new brace fasteners was almost less than 70% in comparison with conventional fastener. In the case of R_e=1.0, some story drifts of 1st floor with the new fastener are higher than the one with conventional fastener. However, the maximum story drift with the new faster is under 2.5% while the one with conventional faster is under 2%, the difference between them is small.

Lately, the number of wooden houses which have nailed plywood wall on the outer face of external wall is increasing. Nailed plywood wall has great influence on shear strength of wooden houses. To examine the influence, analysis model with both brace and nailed plywood wall was built and additional analysis was conducted.

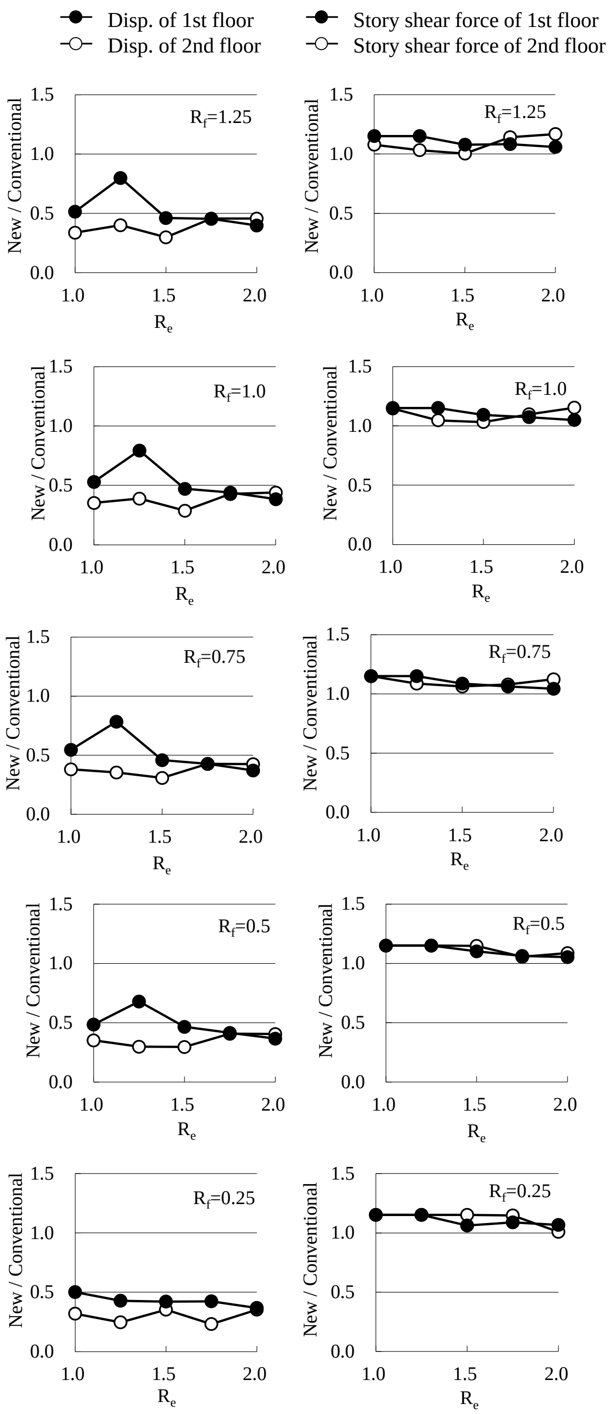
Figure 18 and Figure 19 show earthquake response and ratio of story drift and story shear coefficient when 50% of wall length of wood brace was replaced by plywood shear wall.

Comparing with Figure 14(a), it is found that story drift decreased by 20% by replacing wood brace with conventional fastener with nailed plywood. It is considered that the structural performance of wood brace with conventional brace fastener is over estimated because total wall length after the replacement is the same as the one before the replacement. In the case of the new brace fastener, the replacement by plywood shear wall caused little change in response displacement. It means that seismic performance evaluated from the earthquake response analysis is equivalent to the one of nailed plywood wall.



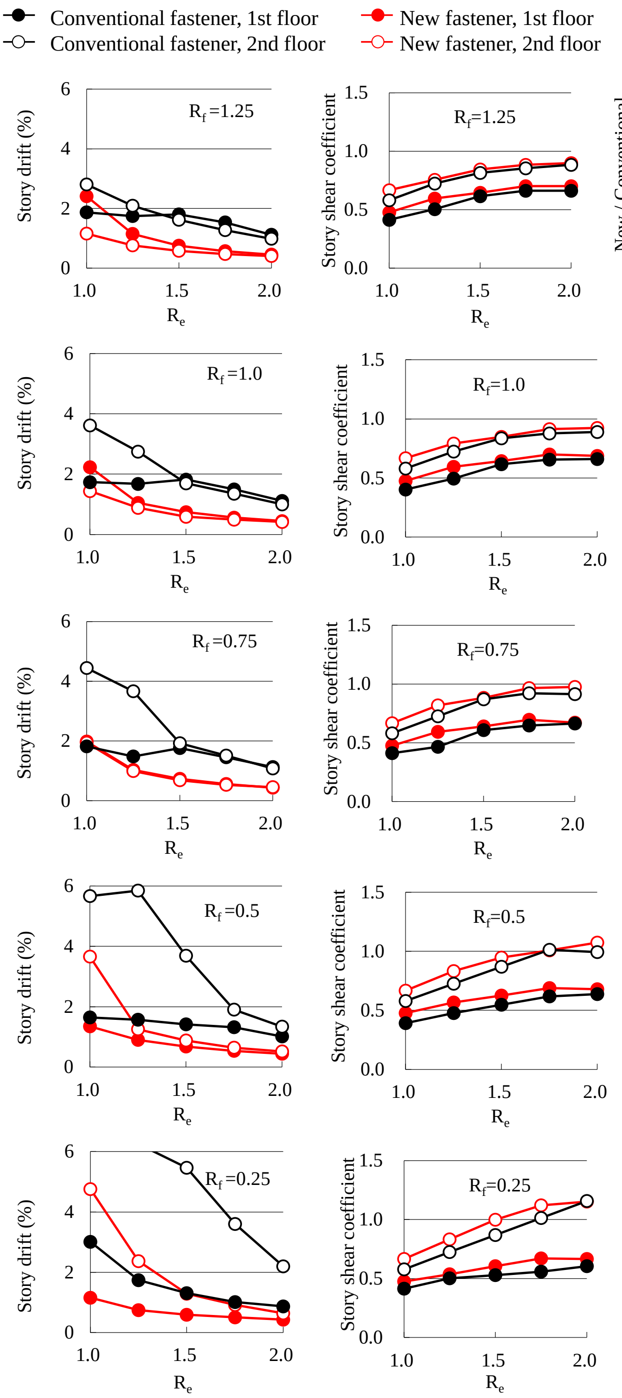
(a) Story drift (b) Story shear coefficient

Figure 14: *Maximum earthquake response under JMA Kobe wave*



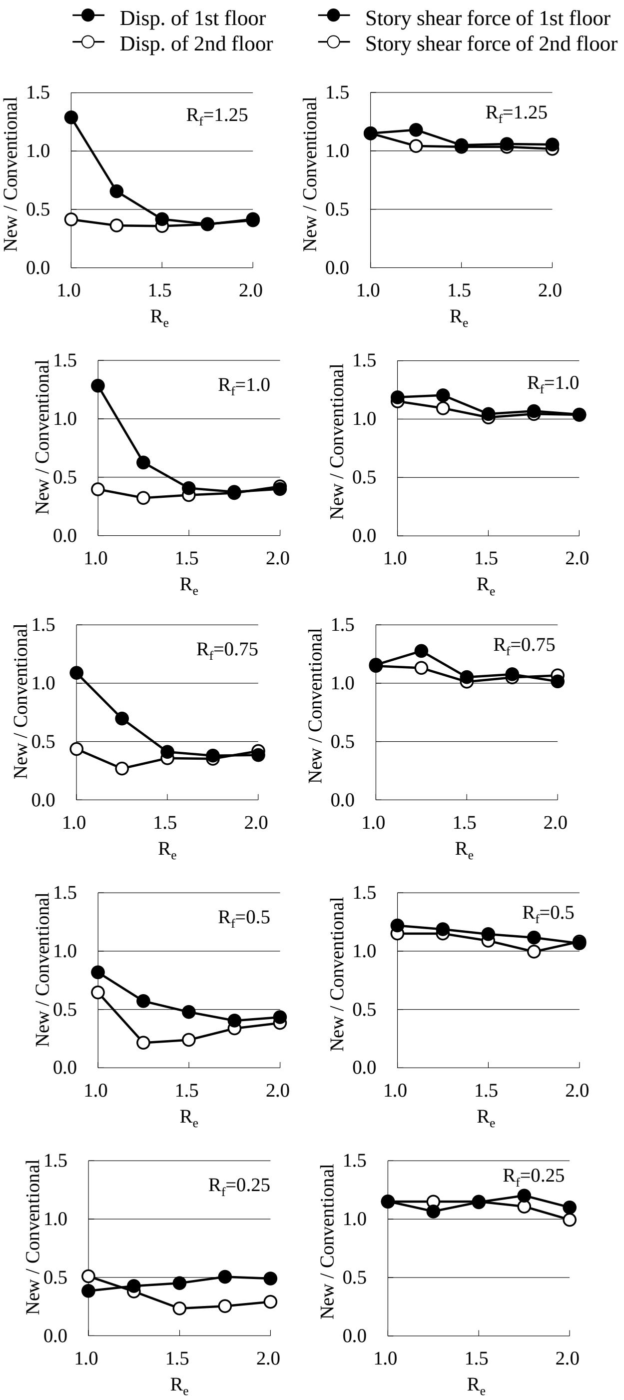
(a) Disp. with new fastener/ conventional fastener (b) Story shear coefficient with new fastener / conventional fastener

Figure 15: *Effect of the new brace fastener under JMA Kobe wave*



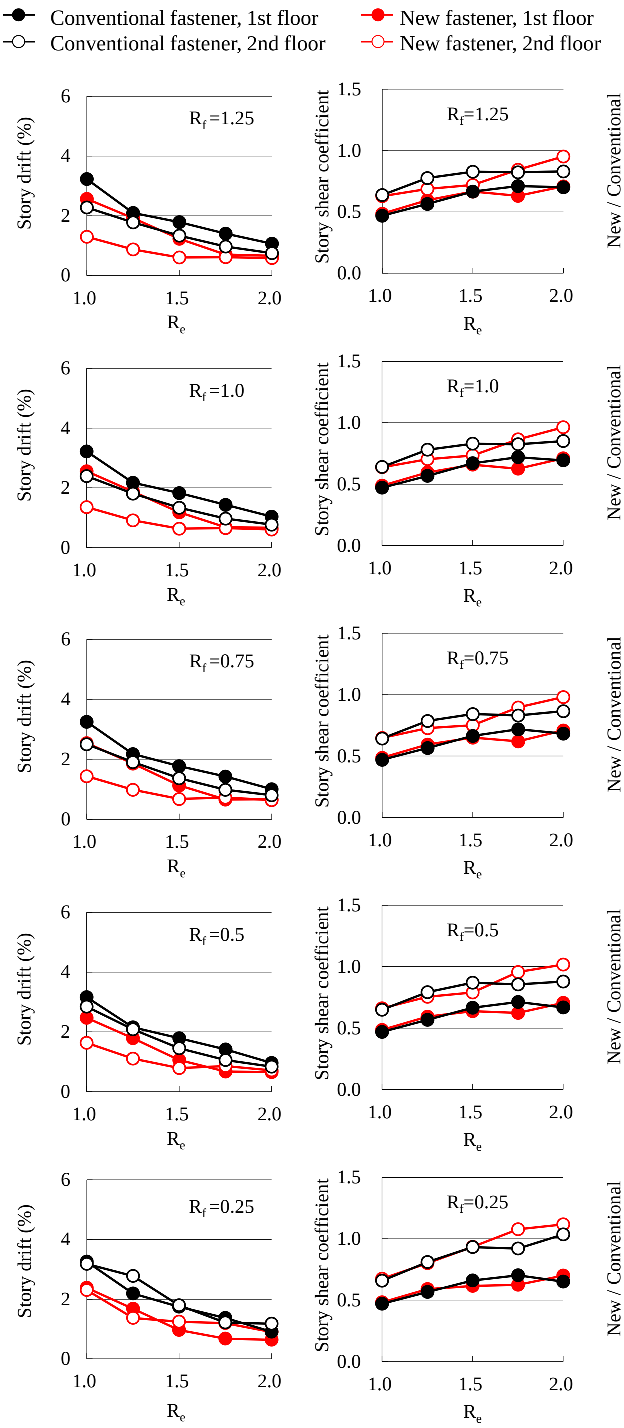
(a) Story drift (b) Story shear coefficient

Figure 16: Maximum earthquake response under BCJ L2 wave



(a) Disp. with new fastener/ conventional fastener (b) Story shear coefficient with new fastener / conventional fastener

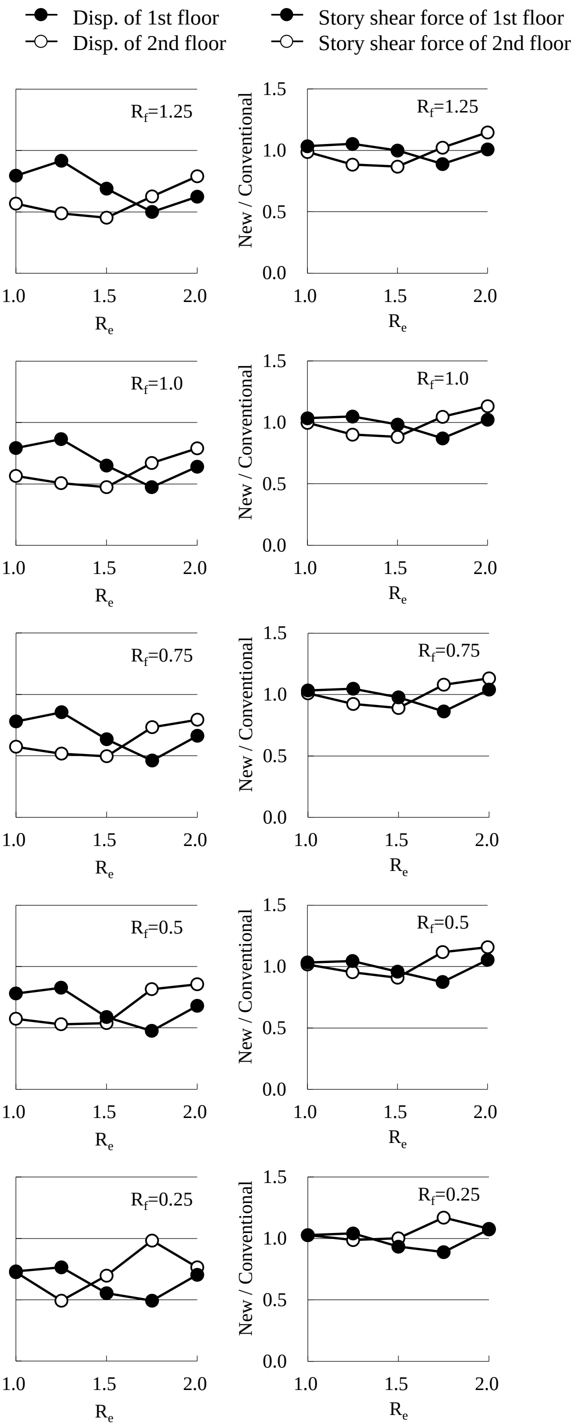
Figure 17: Effect of the new brace fastener under BCJ L2 wave



(a) Story drift

(b) Story shear coefficient

__Figure 18:__ Maximum earthquake response with nailed plywood under JMA Kobe wave



(a) Disp. with new fastener/ conventional fastener

(b) Story shear coefficient with new fastener / conventional fastener

__Figure 19:__ Effect of the new brace fastener with nailed plywood under JMA Kobe wave

6 CONCLUSIONS

The structural performance of the new brace fastener was examined through static shear loading test, incremental analysis and earthquake response analysis. It was found it has not only higher seismic performance but also damping performance from the static shear loading test and incremental analysis. Earthquake response analysis showed that the new brace fastener decreases more than 50% of story drift. Moreover, structural performance of wood brace with the new brace fastener is equivalent to the one of nailed plywood.

Since its manufacturing procedure is simple and the cost is lower than conventional dampers on the market, it is expected that a large number of wooden houses are equipped with the new fastener and safer wooden houses against earthquakes are realized.

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