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VERIFICATION OF THE FRACTURE MECHANISM OF A WOODEN BRACING BEARING WALL WITH CROSS-SECTIONAL DEFECTS

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Abstract

The 2016 Kumamoto earthquake was an earthquake with a maximum seismic intensity of 7, centered on the Kumamoto Prefecture, which seriously damaged many wooden houses. Apropos existing wooden houses which were damaged during this earthquake, there were cases reported where the gypsum board did not exhibit the prescribed shear resistance due to the buckling of braces with cross-sectional defects, and consequently, load-bearing walls were destroyed.

Article 45, paragraph 4 of the Building Standard Act Enforcement Order contains provisions for bracing with notches. However, in spite of that, many examples of existing wooden houses that have been used as load-bearing walls without notch-reinforced cross-bracing bars have been reported.

In past studies, there have been examples of research on the bending strength and stiffness of members with notches and wooden beams. However, there have not been many examples which have focused on full-scale frames using bracing cross-section defects or members with cross-section defects.

Consequently, in order to consider the fracture and mechanical properties, we conducted a fracture mechanism verification experiment of a bracing load-bearing wall with a cross-sectional defect. The verification process was carried out in two parts: i) we conducted element tests of the bracing specimens to confirm their buckling fracture properties. ii) we conducted collapse tests by using a full-scale frame, assuming a damaged bracing bearing wall.

According to the element tests, we established the buckling fracture properties of bracing. It was found that the presence or absence of notches, as well as differences in tree species, affect the strength of bracing. In the full-scale frame test, we found that the presence or absence of notches in the braces used affected the strength of the wall. In addition, by comparing the element test and the full-scale frame test, we also found that the timing at which the compression braces were most damaged was almost identical.

Keywords: existing wooden house, wooden bracing, buckling, full-scale frame test, restoring force characteristic

1. Introduction

The Kumamoto earthquake of April 14, 2016 was an earthquake with a maximum seismic intensity of 7, centered on the Kumamoto Prefecture, which caused many wooden houses to be seriously damaged[1,2]. Regarding the wooden houses damaged during this earthquake, there were several reported cases where the gypsum board did not exhibit the prescribed shear resistance, due to the buckling of braces with cross-sectional defects, the result of which was that load-bearing walls were destroyed.

Article 45, paragraph 4 of the Building Standard Act Enforcement Order says "The bracing shall not be cut off, but not in cases where it is unavoidable to cross." However, in spite of that, several examples of existing wooden houses that have been used as bearing walls without reinforcing the cross-bracing bars with notches, have been reported[2].

In past studies, there have been several examples of research on the bending strength and stiffness of members with notches and wooden beams[3~6]. However, there have not been many examples which focused on full-scale frames by using bracing cross-section defects or members with cross-section defects.

Based on the above, in this study, in order to consider the fracture properties and mechanical properties, we conducted a fracture mechanism verification experiment of a bracing bearing wall with a cross-sectional defect. The verification process was carried out in two parts: i) we performed element tests of the bracing specimens, to confirm the buckling fracture properties. ii) we performed collapse tests by using a full-scale frame assuming a damaged bracing bearing wall.

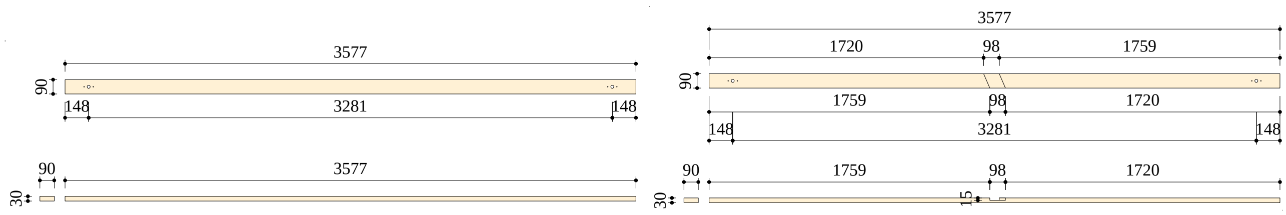
2. Element Tests of the Bracing Specimens

2.1. Specimens

Table 1 summarizes the material details. Fig. 1 shows the outline of the test specimens comprising S1 (cedar) without a notch, and S2-5 with a notch (cedar, Douglas pine, and western hemlock). Based on the dimensions of the actual frame, the bracing had a length between supporting points of 3,281 mm and the notch depth was 15 mm.

Table 1 – Material details

	Notch	Gypsum board	Material type	Material gread
S1	×	×	cedar	E70
S2	○	×	cedar	E70
S3	○	×	douglas pine	E110
S4	○	×	douglas pine	E110
S5	○	×	western hemlock	E110



(a) Specimen with notch   (b) Specimen without notch

Fig. 1 – Overview of test specimens

2.2. Loading System

The loading system is shown in Fig. 2. One end of the bracing is pin-joined to the column and the other end is pin-joined to the actuator. Rollers are installed at two places on the bracing to prevent vertical deflection during the application of force. The front side of the diagram (of Fig. 2) is called the S-side, the back side is called the N-side, the left side is called the W-side, and the right side is called the E-side. The bracing is installed with the notch facing the S-side.

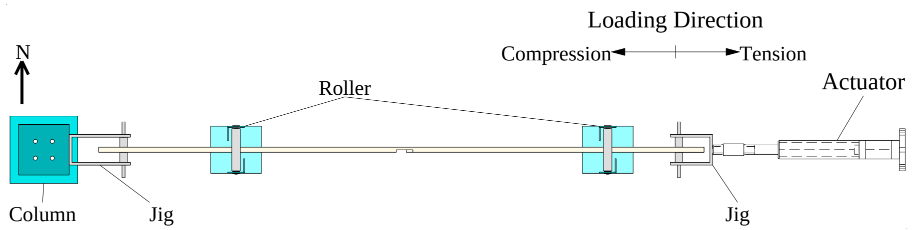


Fig. 2 – Loading system (Plan)

The applied force, a positive and negative alternating repetition of compression and tension, is performed within a range in which the buckled brace can be accommodated in the apparatus. On the compression side, the compression of the bracing corresponds to the amplitude of the story deformation angle of about 1/250, 1/200, 1/180, 1/150, 1/120, 1/100, 1/75, and 1/50 rad, respectively; a displacement of 6.0 mm, 7.5 mm, 8.4 mm, 10.1 mm, 12.6 mm, 15.1 mm, 20.2 mm, and 30.4 mm is applied, respectively; and on the tension side, a force is applied until the load reaches 10 kN.

In order to measure the influence in the in-plane direction and out-of-plane direction, strain gauges are attached 200 mm from the bracing fulcrum and on the four sides around the center.

2.3. Test Results

Fig. 3 shows the main fracture characteristics, and Fig. 4 shows the skeleton curve of the load-axial displacement relationship.

［S1］ After exhibiting a maximum load of 6.4 kN on the compression side of 10.1 mm (1/150 rad), the material buckled and its resistance dropped rapidly. The maximum out-of-plane displacement was 128.7 mm on the W-side and 123.3 mm on the E-side. The bending moment in the out-of-plane direction was a maximum at the center of the bracing when compressed. When a tensile force of 12.6 mm (1/120 rad) was applied, the edge was ‘cut off’, but no other noticeable damage was observed.

［S2］ After exhibiting a maximum load of 4.2 kN on the compression side of 6.0 mm (1/250 rad), the material buckled, and its resistance dropped rapidly. The maximum out-of-plane displacement was 184.3 mm on the W-side and 185.6 mm on the E-side. The bending moment in the out-of-plane direction was a maximum around the notch when compressed. It buckled to the N-side due to the compression-side force, referred to as N-side buckling. At 12.6 mm (1/120 rad) on the compression side, the surface of the notch portion was ‘peeled off’ at the N-side, and at 30.4 mm (1/50 rad) on the compression side, the notch segment was cracked.

［S3］ After exhibiting a maximum load of 1.3 kN on the compression side of 6.0 mm (1/250 rad), the material broke immediately after buckling. The maximum out-of-plane displacement was 188.9 mm on the W-side and 213.6 mm on the E-side. It buckled to the notched S-side, referred to as S-side buckling, and was damaged in the notch at 6.0 mm (1/250 rad) on the compression side.

［S4］ After exhibiting a maximum load of 3.2 kN on the compression side of 6.0 mm (1/250 rad), the material buckled and its resistance gradually decreased. The maximum out-of-plane displacement was 201.9 mm on the W-side and 202.9 mm on the E-side. The bending moment in the out-of-plane direction was a maximum around the notch when compressed. Buckling occurred on the N-side, peeling started on the N-surface of the cutout at 12.6 mm (1/120 rad) on the compression side, and cracked significantly at 30.4 mm (1/50 rad) on the compression side.

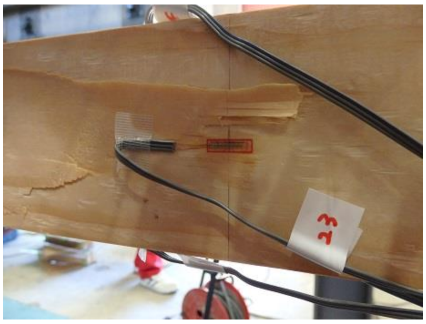
［S5］ After exhibiting a maximum load of 5.8 kN on the compression side of 6.0 mm (1/250 rad), the material buckled and its resistance dropped rapidly. The maximum out-of-plane displacement was 189.0 mm on the W-side and 184.4 mm on the E-side. The bending moment in the out-of-plane direction was a maximum around the notch when compressed. Buckling occurred on the N-side, cracks occurred in the notch at 12.6 mm (1/120 rad) on the compression side, and a relatively small amount of peeling occurred on the N-surface of the notch at 30.4 mm (1/50 rad) on the compression side.


(a) Without notch (1/120 rad)


(b) N-side buckling (1/50 rad)


(c) S-side buckling (1/50 rad)


(d) Notch breakage (+1/250 rad)


(e) Peeling (+1/120 rad)

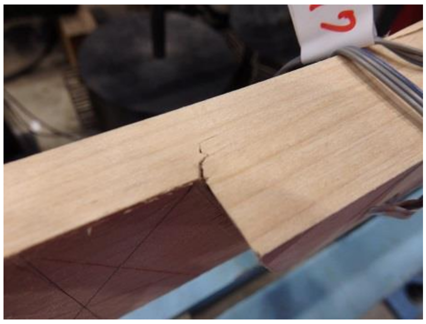

(f) Crack (+1/120 rad)

Fig. 3 – Typical damage of specimens

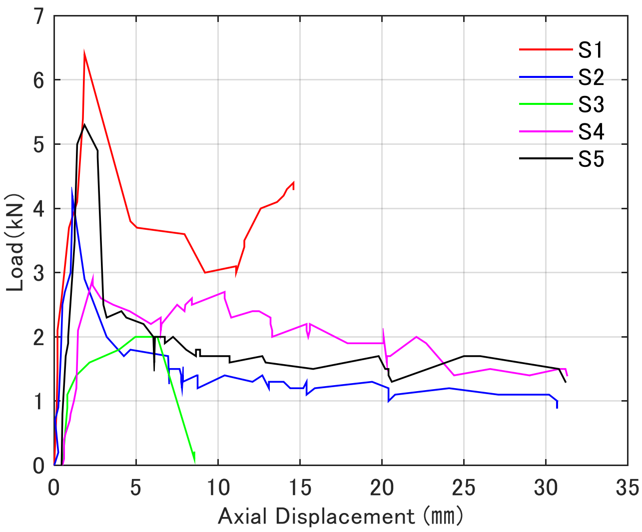


Fig. 4 – Skeleton curve

2.4. Consideration of Perform Element Tests Results

The bracing without a notch was not damaged by buckling, and the bracing with a notch generally resulted in damage to the notch. Regarding the buckling load, the bracing S1 without a notch exhibited the largest buckling load, followed by the bracing S5 with a notch. The bending moment in the out-of-plane direction of the compression side of the bracing showed a maximum at the center of the bracing (around the notch for the bracing with a notch).

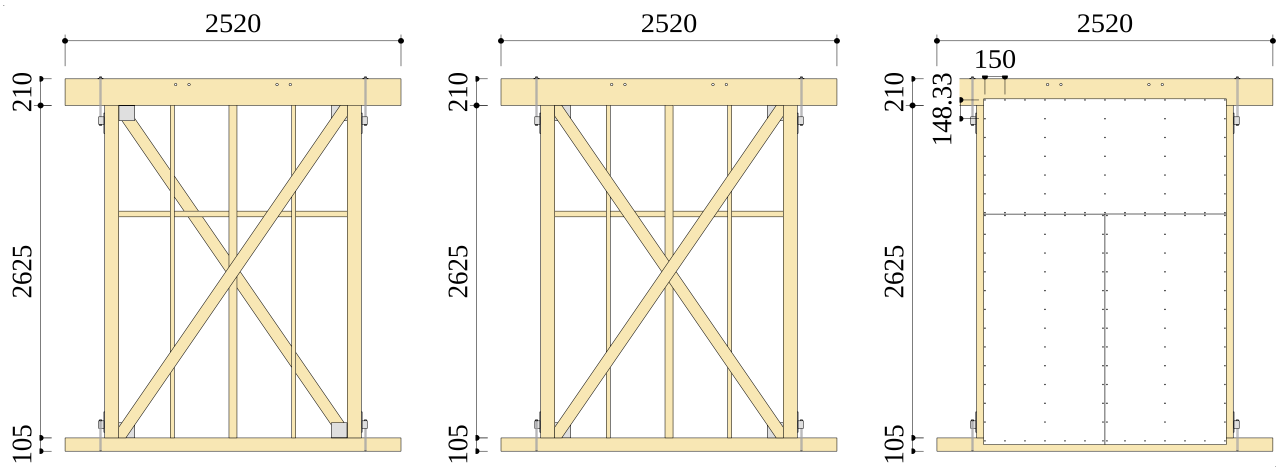
3. Static Loading Test of Brace Frame Specimen

3.1. Specimens

Fig. 5 shows the outlines of the frame specimens, which consist of columns, girders, bases, studs, and bracings, all of which are made of cedar. The basic frame is 1,820 mm × 2,730 mm.

The bracing is assumed to be a two-sided bracing, and there are two specimens, a specimen F1 (without a notch), and a specimen F2 (with a notch). The bracing is 30 mm × 90 mm, and the notch depth is 15 mm, which is the same as that of the element specimens described in Section 2. The ends of the bracing are joined using double braced hardware.

The Gypsum board is 12.5 mm thick, of dimensions 910 mm ×1,820 mm, with 3 pieces pasted on each side. The body edge is placed in the seam, and screws are positioned at intervals of approximately 150 mm. Hole-down hardware specced at 25 kN is installed on the capital and 35 kN is installed on the pedestal, respectively.



(a) F1 detail (b) F2 detail (c) Gypsum board

Fig. 5 – Overview of test specimens

3.2. Loading System

The loading system is shown in Fig. 6. The base of the frame specimen is fixed to a steel frame by means of anchor bolts, the surcharge load being 1 ton per column. A positive/negative alternating force is gradually imposed and increased repeatedly through a jig installed on the top of the frame. The force direction is positive in the left direction (as seen in Fig. 6). Note that the positive column is a W-column and the negative column is an E-column.

A load cell is installed at the applied position on top of the frame specimen, and the horizontal resistance of the specimen is measured. The absolute displacement u at the top of the specimen is measured using a wire displacement meter. The value obtained by dividing the absolute displacement u by the inner height H of the column is defined as the interlayer deformation angle R of the frame. As for the applied force, the amplitude of R is 1/250, 1/200, 1/180, 1/150, 1/120, 1/100, 1/75, 1/50, 1/30, 1/20, 1/15, 1/10, 1/8, 1/6, 1/5 rad, and force is applied until the maximum deformation angle ±1/5 rad is reached or horizontal resistance is lost.

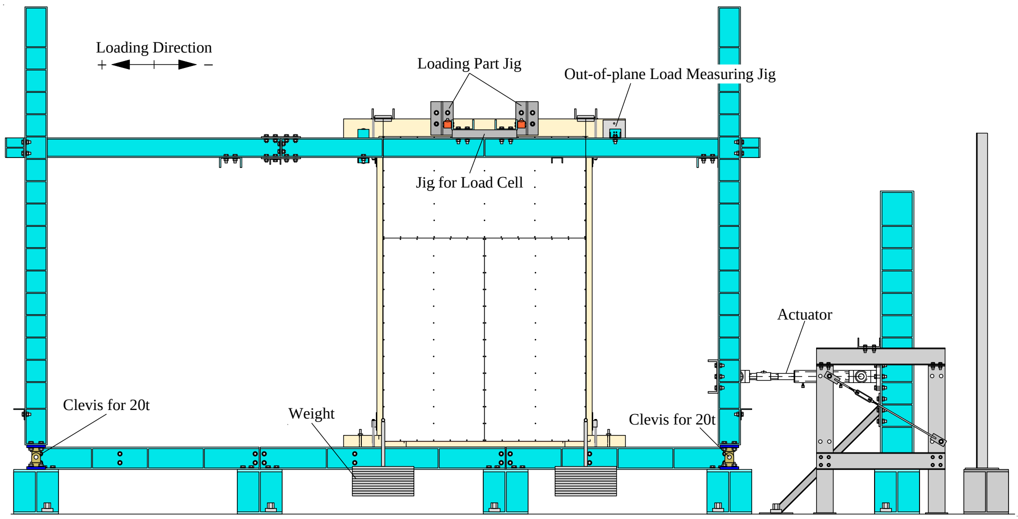


Fig. 6 – Loading system (Elevation drawings)

3.3. Fracture Characteristics

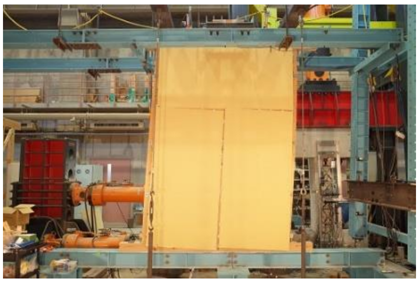
Fig. 7 shows the main fracture characteristics of the samples tested.

［F1］ The maximum strength of the specimen was 33.8 kN on the positive side and 38.5 kN on the negative side, and the deformation angles at the break were 0.020 rad on the positive side and 0.013 rad on the negative side.

The damage became audible at 1/100 rad on the positive side, and louder at 1/50 rad on the positive side. At approximately 1/150 rad, the corners where the gypsum boards were in contact with each other began to get damaged, and the screws from the W-side rows on both sides of the W-side gypsum board attached to the lower section of the frame gradually became detached. Before reaching the negative 1/50 rad, the N-side compression brace broke through the gypsum board. Furthermore, before reaching the second 1/50 rad on the positive side, the lower part of the S-side compression bracing broke, penetrating the gypsum board. The pedestal did not show any noticeable damage. At the time of dismantling, it was confirmed that a screw had broken and a split had occurred where the bracings of the studs on the W and E-sides were in contact.

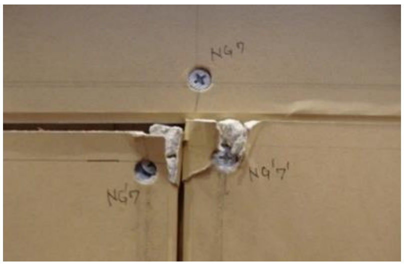
［F2］ The maximum strength of the specimen was 28.2 kN on the positive side and 29.2 kN on the negative side, and the deformation angles at the break were 0.023 rad on the positive side and 0.010 rad on the negative side.

At 1/180 rad on the positive side, the corner of the gypsum board started to get damaged, and at 1/120 rad on the negative side, the damage became audible. After arriving at the 1/50 rad on the positive side, the compression bracing on the S-side broke at the notch and pierced the gypsum board. Furthermore, before reaching the negative 1/50 rad, the N-side compression bracing also broke. The pedestal did not show any noticeable damage. At the time of dismantling, it was confirmed that a split had occurred at the lower end of the S-side bracing.


(a) Before reaching (−1/50 rad)


(b) Before reaching (+1/50 rad)

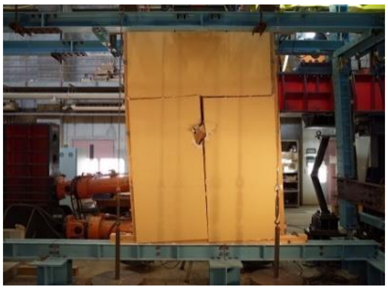

(c) N-side damage

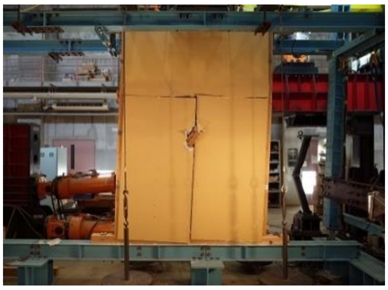

(d) Gypsum board joint damage (1/50 rad)


(e) W-side stud splitting when dismantling


(f) Screw break

(A) Specimen - F1


(a) Reaching (+1/50 rad)


(b) Before reaching (+1/50 rad)


(c) Bracing damage (1/50 rad)


(d) Lower end of N side bracing when dismantling

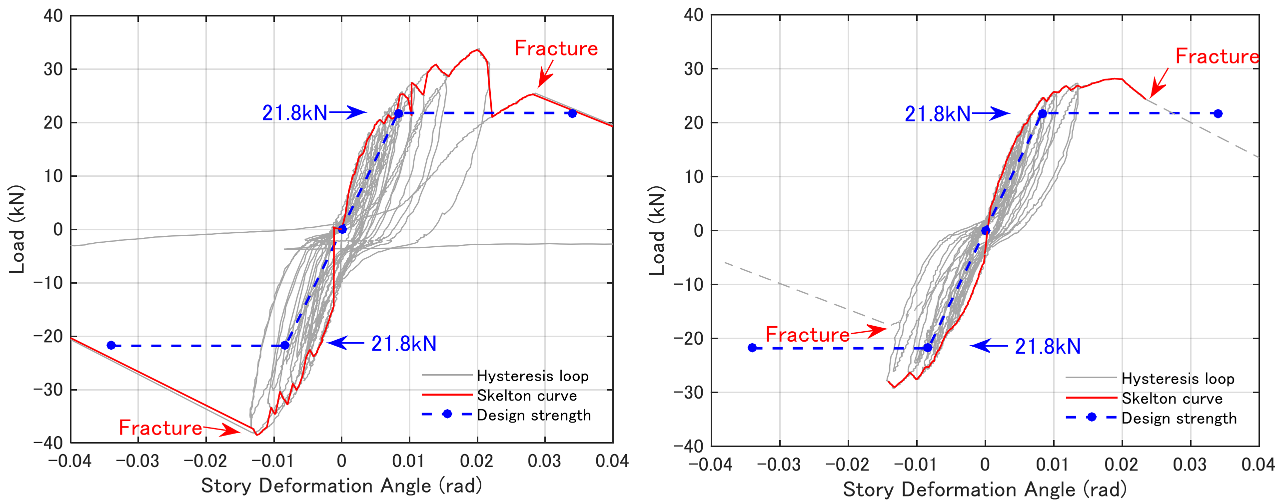

(e) Bracing damage when dismantling

(B) Specimen – F2

Fig. 7 – Typical damage of specimens

3.4. Horizontal load–story deformation angle relationship

The horizontal load–story deformation angle relationship is shown in Fig. 8 where it is compared to the design value[6]. The maximum load for specimen F1 was 33.8 kN on the positive side (at 0.020 rad) and 38.5 kN on the negative side (at 0.013 rad), and for specimen F2 it was 28.2 kN on the positive side (at 0.019 rad), and 29.2 kN on the negative side (at 0.013 rad). The designed value was 21.8 kN at 1/120 rad and reaches the deformation limit at 1/30 rad. Comparing the design values with the experimental values, both the frame specimens exceeded the maximum strength but exhibited low deformation performance. A comparison of the two specimens showed that the provision of the notch in the bracing reduced its maximum strength. In both cases, the bracing buckled at a story deformation angle of 1/50 rad, and broke the gypsum board causing a decrease in the restoring force. However, in the case of a bracing with a notch, the bracing was broken as inferred by the difference in maximum strength.



(a) Specimen - F1 (b) Specimen - F2

Fig. 8 – Restoring force characteristics

4. Comparison Between Element Test and Full-scale Frame Experiment

The most prominent damage timing of the compression bracings was approximately equal to 1/50 rad in both tests. Moreover, in both tests no noticeable damage was observed in the bracing without a notch, and in the bracing with a notch, cracks or breakage occurred during compression.

5. Conclusion

In this study, a gypsum board wall was subjected to a specified shear resistance due to the buckling of a bracing with the cross-sectional defect of an existing wooden house, reported in an earthquake with a maximum seismic intensity of 7, in the Kumamoto Prefecture, on April 14, 2016. Focusing on the case where a force could not be exerted, a verification experiment was conducted, and the fracture mechanism of the braced load-bearing wall having a cross-sectional defect was considered.

6. Acknowledgement

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