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THE EVALUATION OF RESTORING FORCE OF DIFFERENT SASHIGAMOI JOINT IN TRADITIONAL WOODEN RESIDENTS

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Abstract

There are many traditional wooden houses that have a unique appearance in Japan. According to differences in regional characteristics and historical culture, there are various specifications in the joint. Due to the cross-sectional defect of joint, damage often occurs near the joint during an earthquake. So, it is very important to accurately evaluate the behavior of joints during earthquakes in order to ensure the earthquake resistance of traditional wooden houses.

One of the calculation methods currently used in the evaluation of seismic performance of traditional wooden houses is the calculation of critical strength. However, in this method, the restoring force characteristics of the entire building are estimated by simply adding the shear force given to each seismic element without considering the different shape of joint. In a frame having a joint with a large cross-section beam (called *Sashigamoi*), the inter-column distance is geometrically shortened with an increase in the interlayer deformation angle, so that an axial force is generated in the large cross-section beam. As a result, there is a concern that the restoring force and stress state of the frame were changed, and damage might occur near the joint. Therefore, in order to properly evaluate the seismic performance of traditional wooden houses, it is necessary to understand the effects of various specifications of joints on the destructive properties and restoring force characteristics.

From the above, in this study, we performed bending experiments on 8 specimens with different joint shapes to understand the mechanical characteristics of the joints. In addition, based on the existing estimation formula, we proposed a restoring force estimation formula considering the axial force generated in the beam and compared it with the experimental results.

Keywords: traditional wooden houses, joints, mechanical characteristics, restoring force, estimation

1. Introduction

According to regional characteristics and cultural differences, there are various specifications in joint in Japan. In the limit strength calculation, which is one of calculation methods used in the seismic performance evaluation of traditional wooden residents, the shear forces of all earthquake resistant elements are simply added, and the restoring force is given for each seismic element without considering the different detail of joints. In this study, to figure out the effect of different proportions on restoring force characteristics, we performed bending test on 4 specimens. Furthermore, based on the restoring force estimation formula we proposed in past study, we modeled different joints of 4 specimens and compared the results of simulation with the experiments to investigate the accuracy of the simulation.

2. Outline of bending test

2.1 Specimens

As shown in Fig.1, four specimens were extracted from the frame and designed in same dimension method. The columns (120mm×120mm) were made from cedar wood, boxed heart timber. The beam(120mm×270mm) were made from pine wood, free of heart center timber. Table.1 summarizes the material type of four specimens and the Young's modulus estimated from material test carried out by cutting out test pieces after disassembling the specimen.

To compare with the past study[1], the joint shape of three specimens are Hanhozo-Komisendome(T-1), Hikidokko-Syachisen(T-3) and Sagekama-Kusabi(T-4), as same as the joint shapes in the past study but in different propotion, as shown in Fig.2(a)(c)(d). The shape of specimen T-2 was same with specimen T-1, but the column was inserted with two beam from two directions, as shown in Fig.2(b).

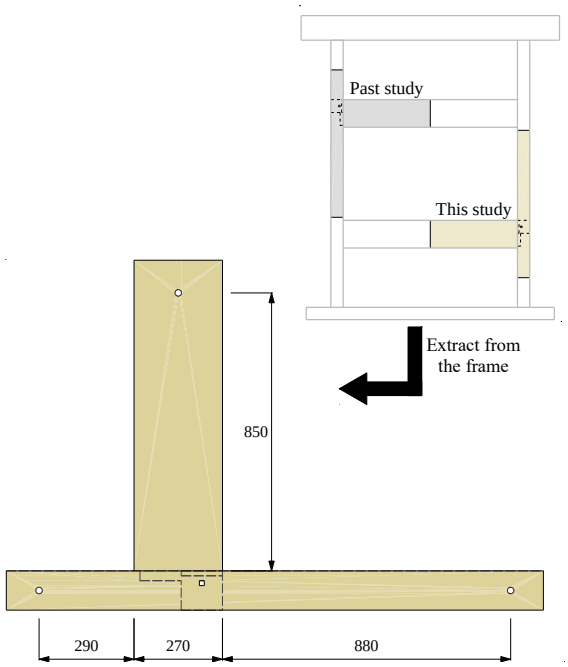


Fig. 1 – Specimen

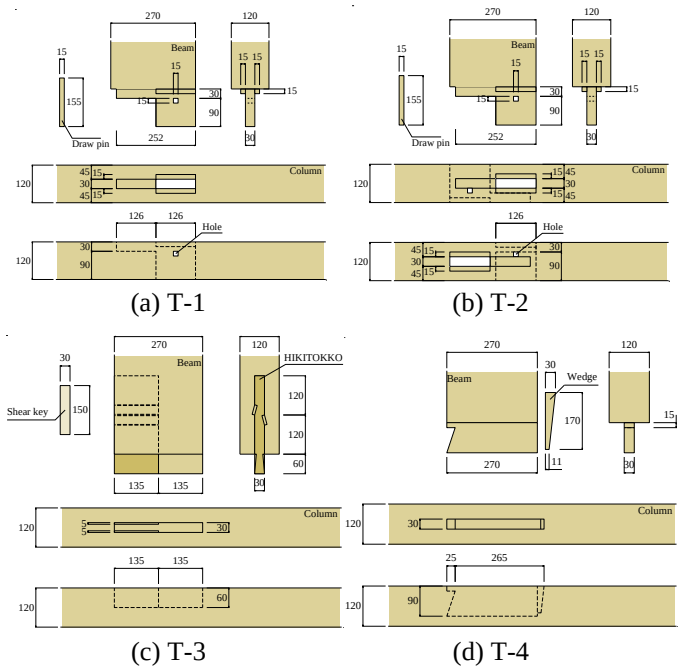


Fig. 2 – Detail of each specimen

2.2 Loading system

The specimen is placed so that the column was horizontal, and the beam was vertical. Both ends of the column is fixed to the steel frame as pin and pin roller. To apply force, the actuator, attached a jig to the tip, was fixed between the steel frame and specimen beam., as shown in Fig.3 and Photo.1. Also, we use 6 displacement-transducer to measure the rotation angle θ during the experiment. The value obtained by dividing the displacement of the actuator by the internal height of the column is defined as the deformation angle R of the specimen. Bending test was applied to the specimen such that the amplitude of R in the order of 1/120, 1/100, 1/75, 1/50, 1/30, 1/20, 1/15, 1/10, 1/8, 1/6 rad. For the analysis, the right side of Fig.3 was assumed to be the positive direction.

To simulate the phenomena occurring in the actual framework, we also connected a PC-steel bar with load-cell between force applied point, and the intersection of column and beam. An axial force was generated in the beam when the PC-steel bar was inclined and measured by the load cell.

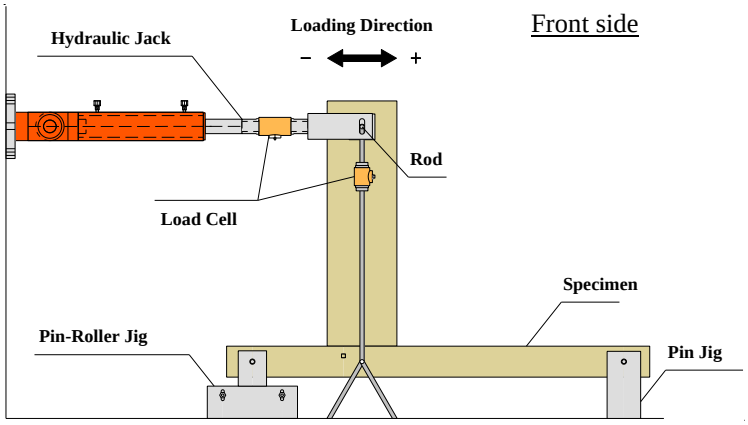


Fig. 3 – Loading system

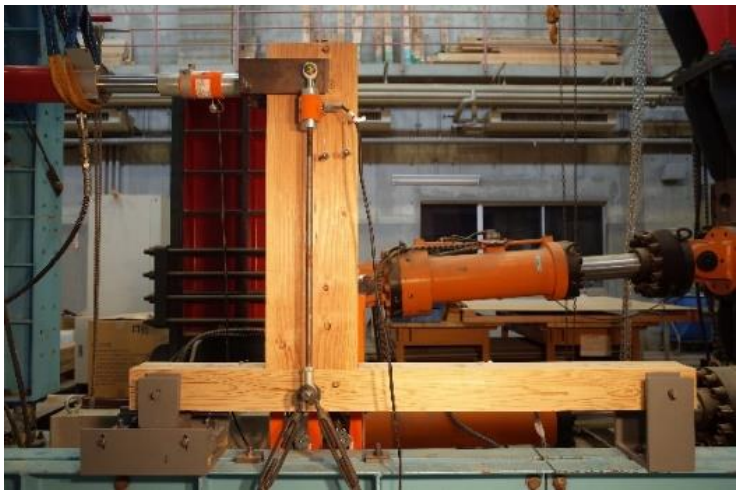


Photo 1 – Loading state

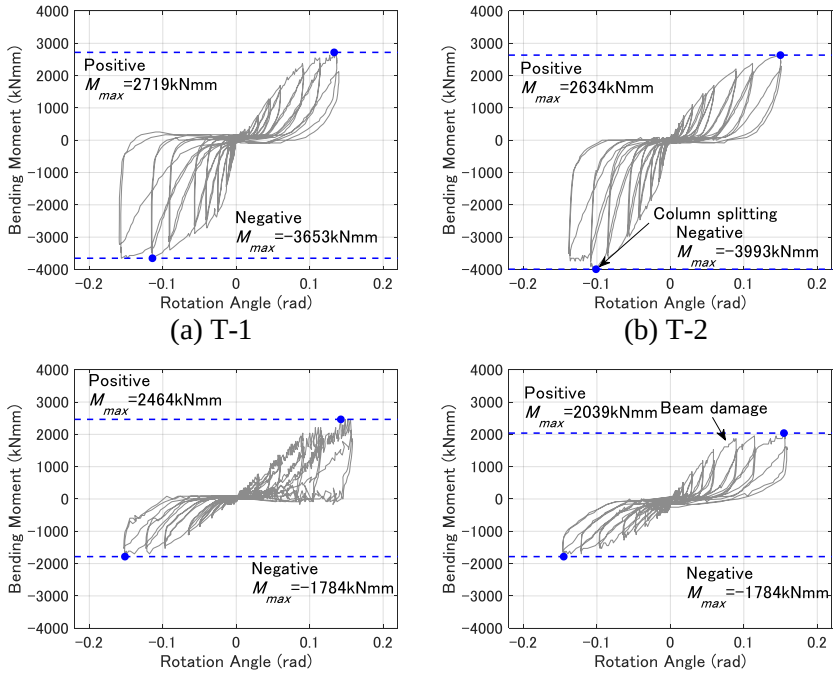
Table 1. Material property

	T-1		T-2		T-3		T-4	
	Beam	Column	Beam	Column	Beam	Column	Beam	Column
Kind of timber	cedar	pine	cedar	pine	cedar	pine	cedar	pine
Young's modulus (kN/mm^2)	14.1	13.4	14.8	14.2	12.1	12.2	13.0	11.2

3. Results of bending test

The relationship between bending moment M and joint rotation angle θ is shown in Fig.4, where black lines indicate the hysteresis loops of the specimen. And the damage of specimens is shown in Photo.2.

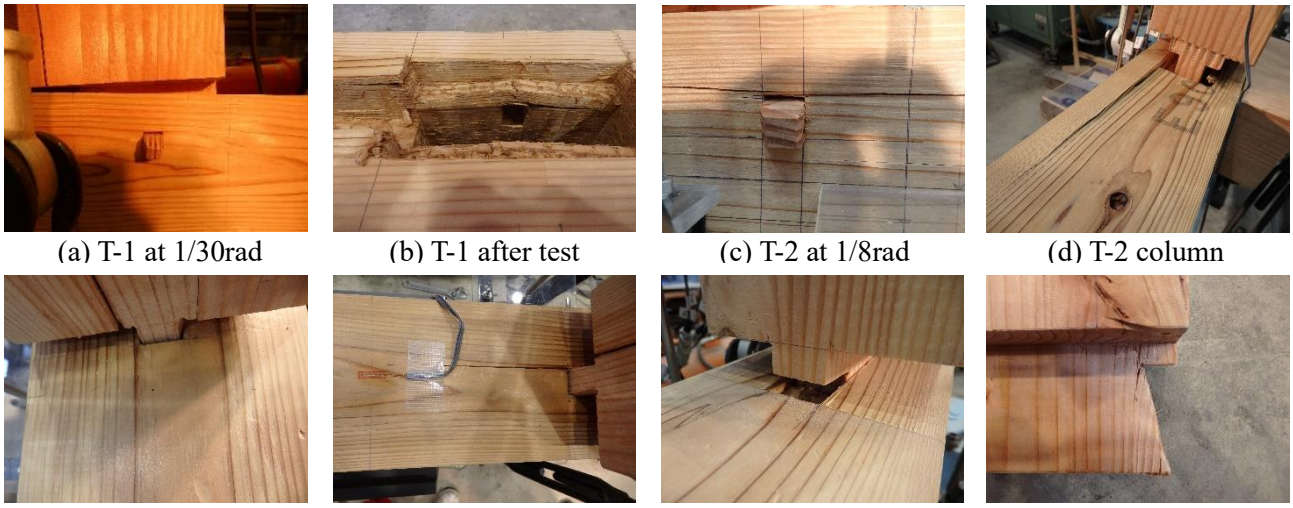
For T-1 specimen, the draw pin started to bent from 1/30 rad, and it was bent further with the breaking sound of the wood at 1/15rad. It was confirmed that fiber splitting occurred in the column after the test. For T-2 specimen, there was no significant damage occurred until 1/15 rad applied. At 1/8 rad, the draw pin hole of the column was split, and the column surface was also split. For T-3 specimen, the column cracked at 1/20 rad. After that, the cracks of the column further splited at 1/15 rad and 1/10 rad. For T-4 specimen, the bending test proceeded without any visible damage until a split occurred in the notch of the beam at 1/10 rad. Later, the damage of the notch progressed, and the bending test was ended at 1/6 rad.



(a) T-1 (b) T-2

(a) T-3 (b) T-4

Fig. 4 – Relationship between bending moment M and joint rotation angle θ



(a) T-1 at 1/30rad (b) T-1 after test (c) T-2 at 1/8rad (d) T-2 column

(e) T-3 at 1/20rad (f) T-3 at 1/10rad (g) T-4 damaged notch (h) T-4 after test

Photo 2 – Damages of specimens

4. Simulation analysis

An analytical model is proposed for the purpose of reproducing differential behavior of joints with different specifications, and displacement incremental analysis, based on the restoring force estimation formulas we proposed in past study[1], is performed as a simulation of static horizontal load test to verify accuracy.

4.1 Assumptions

Based on [2], set a spring with bilinear restoring force, and construct an analysis model based on the following assumptions:

a) Consider the large deformation area and concentrate the deformation at the end of the material.
b) The resistance elements are the resistance of sinking parts, frictional resistance, shear resistance of draw pin and compression resistance of inclined shear key.
c) Indentation occurs only in the orthogonal direction of the wood fibers.
d) The length of sinking part is half of the part inserted into the column.
e) Frictional resistance only includes kinetic friction.
f) Symmetrical two-sided shear works on draw pin.
g) The spring acts only on compression
h) The column and beam are replaced with line member on the material axis.

In order to simulate the experiment, the node points of the column are pin nodes of 1 degree of freedom and pin roller nodes of 2 degrees of freedom . The node point of beam is free end with three degrees of freedom. Column and beam are replaced by an element with material properties and cross section information, connect by springs and rigid ring (rigid elements without considering the deformation) between nodes. In addition, material properties of columns and beams are set using values estimated from material experiments conducted.

4.2 Restoring Force Characteristics of Resistive Spring

The resistance of sinking part is assumed to be a triangular displacement. The relationship between sinking resistance P that occurs when deformation is concentrated at the end of the material and sinking displacement δ, the yield deformation angle θ_y can be expressed by the following equation [3].

$$P = \frac{x_p y_p C_y E_{90}}{z_0}\left[\frac{1}{2} + \frac{2z_0}{3x_p}\left\{1 - exp\left(\frac{-3x_1}{2z_0}\right)\right\}\right]\delta \tag{1}$$

$$\theta_y = \frac{z_0 F_E}{x_p E_{c90}\sqrt{C_x C_y C_{xm} C_{ym}}} \tag{2}$$

Where x_p, y_p, z_0 are the length, width and thickness of the sinking part. E_{90} is the Young's modulus in wood fiber orthogonal direction. The coefficients C_{xm}, C_{ym}, C_x, C_y, F_E are given [3].

The frictional resistance is determined from the sinking resistance P and the friction coefficient μ (= 0.4) by the following equation. Also, the yield deformation angle of frictional resistance θ_f is assumed to be equal to Eq. (1)

$$F_f = \mu P \tag{3}$$

$$\theta_f = \theta_y \tag{4}$$

The shear stiffness of draw pin K_t and the yield strength P_y of the shear resistant spring are calculated by the following equation. Also, the stiffness K_1, K_2 between the main material and the base material and the load P_y according to the fracture mode i are calculated from [3].

$$K_t = \frac{2K_1 \cdot K_2}{K_1 + K_2} \tag{5}$$

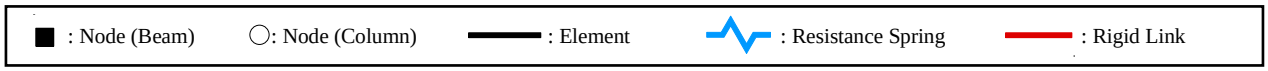
$$P_y = min\,(P_y(i)) \tag{6}$$

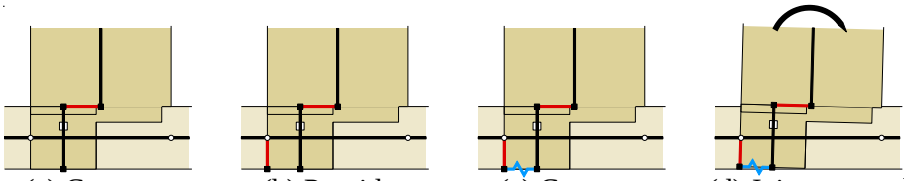
4.3 Modeling of resistance on joint

Taking the T-1 specimen as an example, Fig.5 shows the process for modeling the resistance generated at the joint.

a) Create nodes for beam and column and connect them with beam element.
b) Provide rigid link from the column node towards the outer edge of the column.
c) Connect the node of beam and rigid link with the sinking resistance spring at the area where sink occurs.
d) Compressive force acts on the spring when the joint rotates.

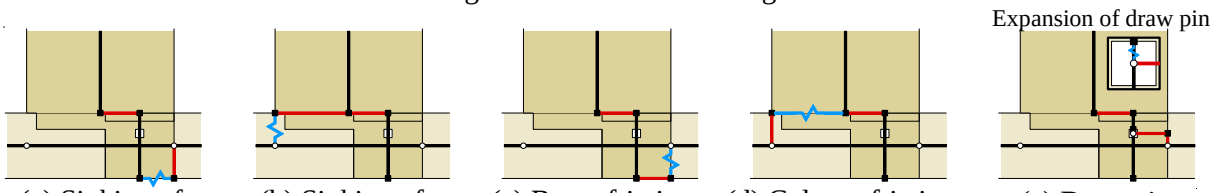
Also, the spring model of the resistance generated at each joint during positive side application are shown in Fig.6 ~ Fig.9.





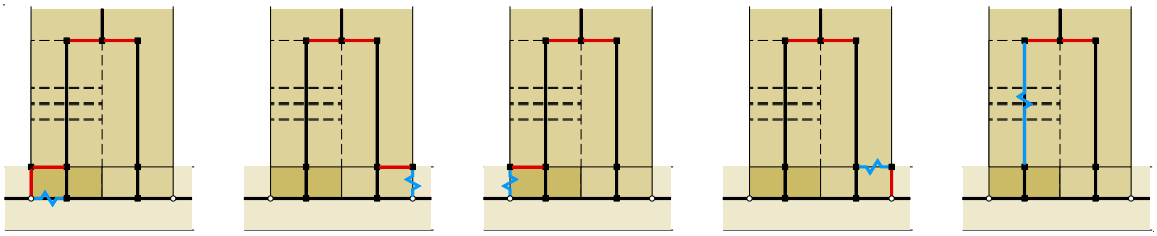
(a) Connect elements (b) Provide rigid link (c) Connect with spring (d) Joint rotates

Fig. 5 – Process of modeling



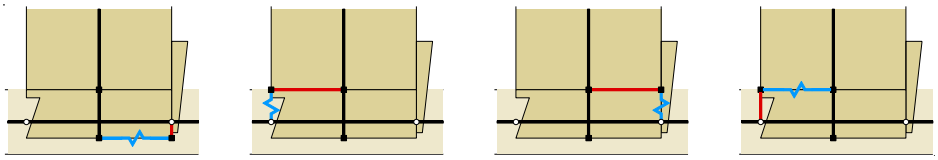
(a) Sinking of beam (b) Sinking of column (c) Beam friction (d) Column friction (e) Draw pin resistance

Fig. 6 – T-1, T-2



(a) Sinking of beam (b) Sinking of column (c) Beam friction (d) Column friction (e) Shear keys resistance

Fig. 7 – T-3

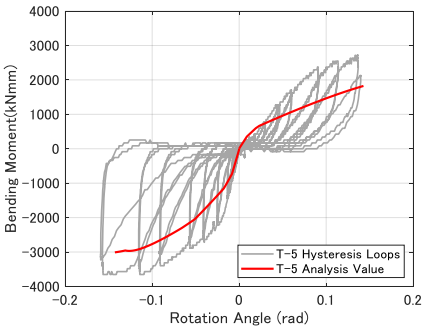


(a) Sinking of beam (b) Sinking of column (c) Beam friction (d) Column friction

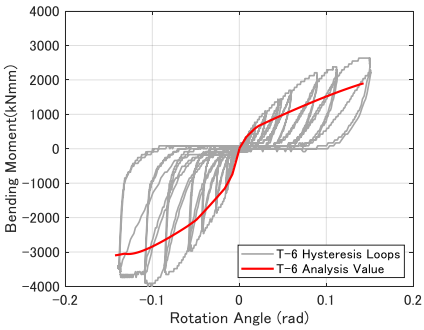
Fig. 8 – T-4

5. Comparison with bending test results

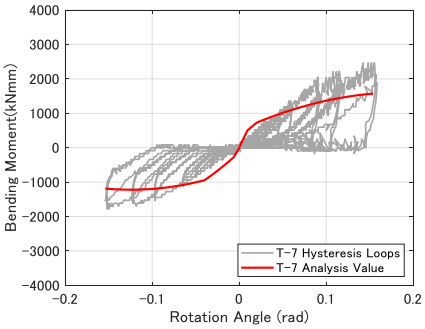
The comparison between the analysis results and the experimental results, and the evaluation results of each specimen are shown in Fig.9 and Fig.10



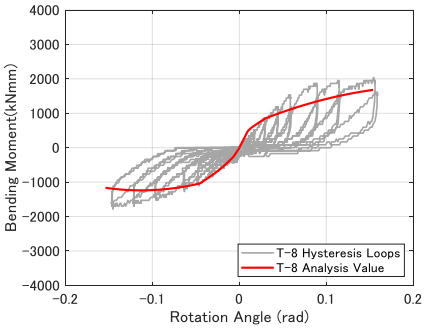
(a) T-1



(b) T-2

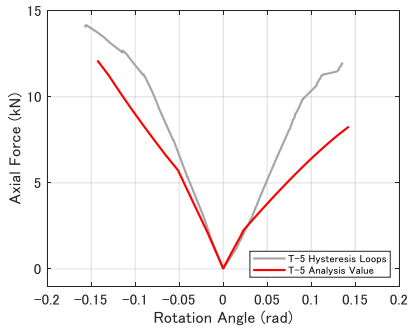


(a) T-3

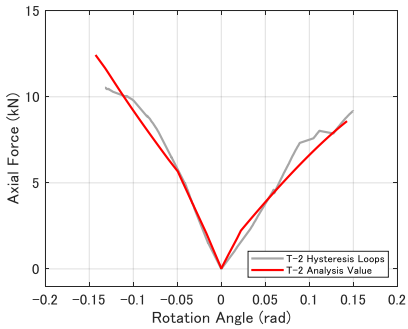


(b) T-4

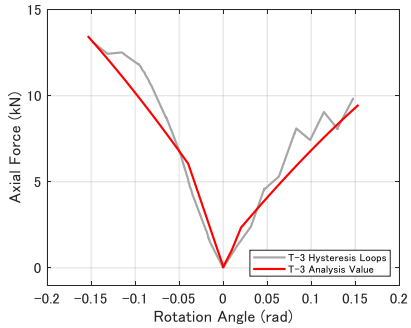
Fig. 9 – Analysis result of bending moment



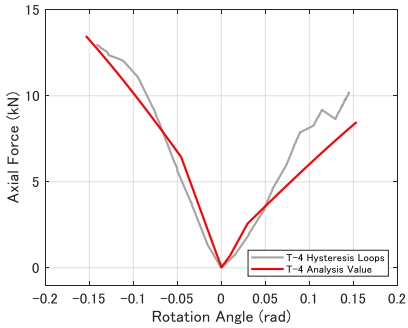
(a) T-1



(b) T-2



(a) T-3



(b) T-4

Fig. 10 – Analysis result of axial force

For T-1 specimen, the initial stiffness of analysis result, which is shown in Fig.9(a) with red line, generally correspond with the experimental result. As shown in Fig.10(a), the axial force of Analysis result in negative side is generally in a good agreement with the experimental result.

For T-2 specimen, as shown in Fig.9(b), the initial stiffness of analysis result correspond with the experimental result, but the ultimate strength is less than it. For axial force, the analysis result in both sides are correspond with the result of experiment well.

For T-3 specimen, the analysis result of both restoring force characteristics and axial force are in a good agreement with the experimental result, as shown in Fig.9(c) and Fig.10(c).

For T-4 specimen, on the both sides, the analysis result almost reproduce the experimental values, Fig.9(d). For axial force, the analysis results on negative sides less than the experimental result, but correspond with the experimental result well on positive sied, as shown in Fig.10(d).

6. Conclusions

In order to figure out the effect of different proportions on restoring force characteristics, we performed bending test on 4 specimens as the same way as the past study. After the bending test, the analytical models of four specimens with different joint shapes were proposed and verified the accuracy by performed displacement incremental analysis as simulation of experiment. The major findings from this study are summarized in the following section:

i. For the restoring force characteristics, the analysis results were estimated to the safe side. The initial stiffness of all specimens generally reproduced with the experimental results, which confirmed the reliability of the model.

ii. In the axial force, there were some cases where the experimental results can be generally reproduced, and there were also some cases where less than the experimental result.

7. Acknowledgements

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8. References

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