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NONLINEAR ANALYSIS OF JAPANESE TRADITIONAL WOODEN FRAMES WITH FITTING-TYPE JOINT

NAOTO IDATE, YUKIMASA YAMADA and NORIKO TAKIYAMA

Division of Architecture and Urban Studies, Tokyo Metropolitan University, Tokyo, Japan

This paper reports our research project on the seismic performance of traditional wooden frames with large-section beams. First, based on past cyclic loading tests on four frames, a simple analysis model of a fitting-type joint was constructed using beam elements. Next, past experimental results were simulated by the model. Finally, a sensitivity analysis was performed to study about the effect of height arrangement of beams on the performance of the whole frame. The major findings of this study are as follows: (a) Some material tests are conducted for wooden test pieces cut down from all column of specimens. The compressive spring properties are decided. (b) Analysis models are constructed, and the restoring forces of frame specimens are simulated precisely. (c) The relation between height arranging beams and the change in restoring force is considered by sensitivity analysis.

Keywords: Traditional wooden structure, Fitting-type joint, Large-section beam, Material test, Nonlinear analysis, Sensitivity analysis.

1 INTRODUCTION

Numerous earthquakes have occurred in Japan. The 1995 Hyogoken-Nanbu Earthquake (M7.3) damaged many structures. Subsequently, there have been many reports of wooden structures collapsing as a result of large earthquakes. Damage to traditional wooden structures often occurs around the joints. Therefore, it is essential to conduct studies on the seismic resistance of joints.

In a seismic evaluation method based on strength-limit calculation, a shear force having a one-to-one correspondence with a load-bearing element is defined, and the shear force of construction only adds to the restoring forces of the element (Editorial 2008). However, there are various joint shapes and types of materials within a single load-bearing element, and the calculation method does not depend on them.

Therefore, we aimed to understand the seismic performance of wooden frames with uneven, large-section beams, and to study the influence of beams on the behavior of the whole frame. In a past study, we conducted a cyclic loading test on four test frames (Takiyama 2015a). Moreover, we constructed a simple analysis model of column-beam joint by using beam elements and compressive springs. Then, the initial stiffness was simulated by linear analysis (Takiyama 2015b). In this study, we simulated skeleton curves of restoring forces by a nonlinear analysis that used material characteristics verified by material tests.

2 OUTLINE OF ANALYSIS

First, the material characteristics are verified by material tests. Next, a model is proposed to simulate the result of past cyclic loading test on four test frames by nonlinear analysis. Here, material nonlinearity and geometric nonlinearity are considered.

2.1 Specimen Design

We designed four specimens based on a typical traditional wooden frame, as shown in Figure 1 and conducted a cyclic loading test based on past studies (Takiyama 2015a, b). Specimen F is the standard frame. Specimen S1 is a frame with a large-section beam. Specimens S2 and S3 are two-span frames with beams. The uneven beams of specimen S3 are exaggerated. After the cyclic loading test, bending test and longitudinal compressive test are conducted on test pieces from all columns based on Japanese Industrial Standard “JIS Z 2101.” The material strength of the columns are indicated in Table 1.

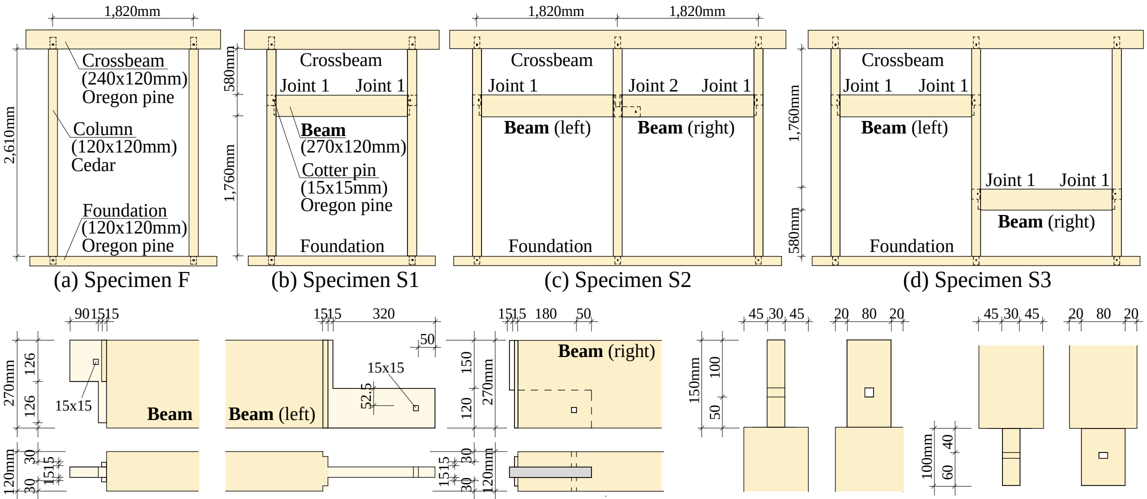


Figure 1. Details of specimens.

Table 1. Material Strength of columns.

Specimen	Column	Strength (N/mm^2)		Young’s Modulus (kN/mm^2)	
		Bending	Compressive	Bending	Longitudinal Compressive
F	Left	71.004	56.755	12.908	10.166
	Right	74.683	55.966	13.858	11.346
S1	Left	54.377	38.927	8.820	8.373
	Right	52.906	41.124	8.806	7.456
S2	Left	66.443	45.442	11.208	9.440
	Middle	67.914	51.200	12.297	11.953
	Right	52.906	41.646	10.006	9.466
S3	Left	48.345	42.286	8.938	8.192
	Middle	56.952	38.682	10.376	8.515
	Right	42.238	50.379	6.509	7.107

2.2 Elements of the Analysis Model

The spring has a bilinear restoring force. The following assumptions were made:

a) The analysis is conducted for large deformations. Deformations are concentrated on the edge of members. After calculation, the damaged member is checked for stress such as breakage or shear fracture parallel to the grain.

b) The resistance elements are the compressive strain resistance of the fiber orthogonality, frictional resistance, and shear resistance of the cotters.

c) The compressive strain occurs only in the direction of the fiber orthogonality. Triangular displacement compression occurs in the tenon (Architectural 2009). Embedment resistance on the tenon is a triangular displacement embedment and the embedded length is half of the tenon length.

d) For the frictional resistance, only the dynamic frictional force is considered. The frictions that occur are the encroaching and sliding frictions.

e) Two symmetrical double shears act on the cotter.

f) Only compressive strain acts on the springs; the spring properties were obtained from the literature (Architectural 2009).

g) All of the members were represented by wire rods on the materials axis.

h) The second stiffness is 1/10 times the first stiffness.

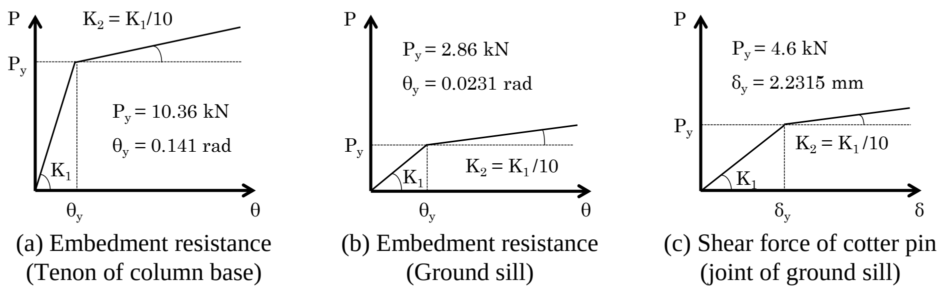


Figure 2. Examples of restoring force of resistance element.

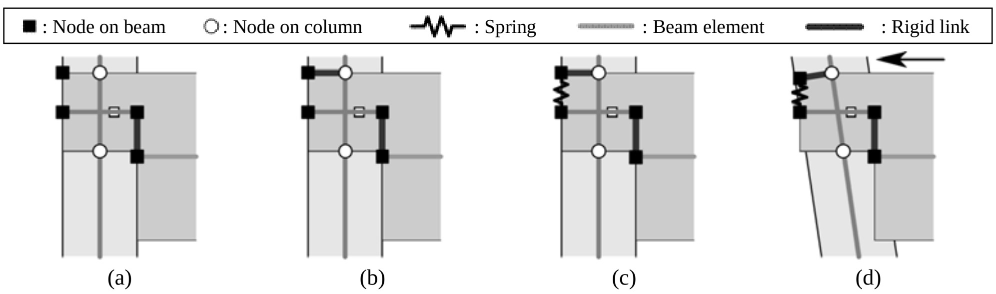


Figure 3. Example of modeling resistance for column-beam joint in positive loading.

First, the nodes were determined for the columns, beams, crossbeams, and base. The nodes on the base were fixed, while others had three degrees of freedom. Next, the columns and horizontal members were replaced with beam elements that have material properties and a cross-section. The two nodes were connected by a rigid link and a spring; the rigid link is a rigid element.

The material properties of the columns are decided based on Table 1. For other materials, these are decided from mechanical stress grade (Architectural 2006).

From the above, some examples of restoring force of resistance element on the column base are shown in Figure 2.

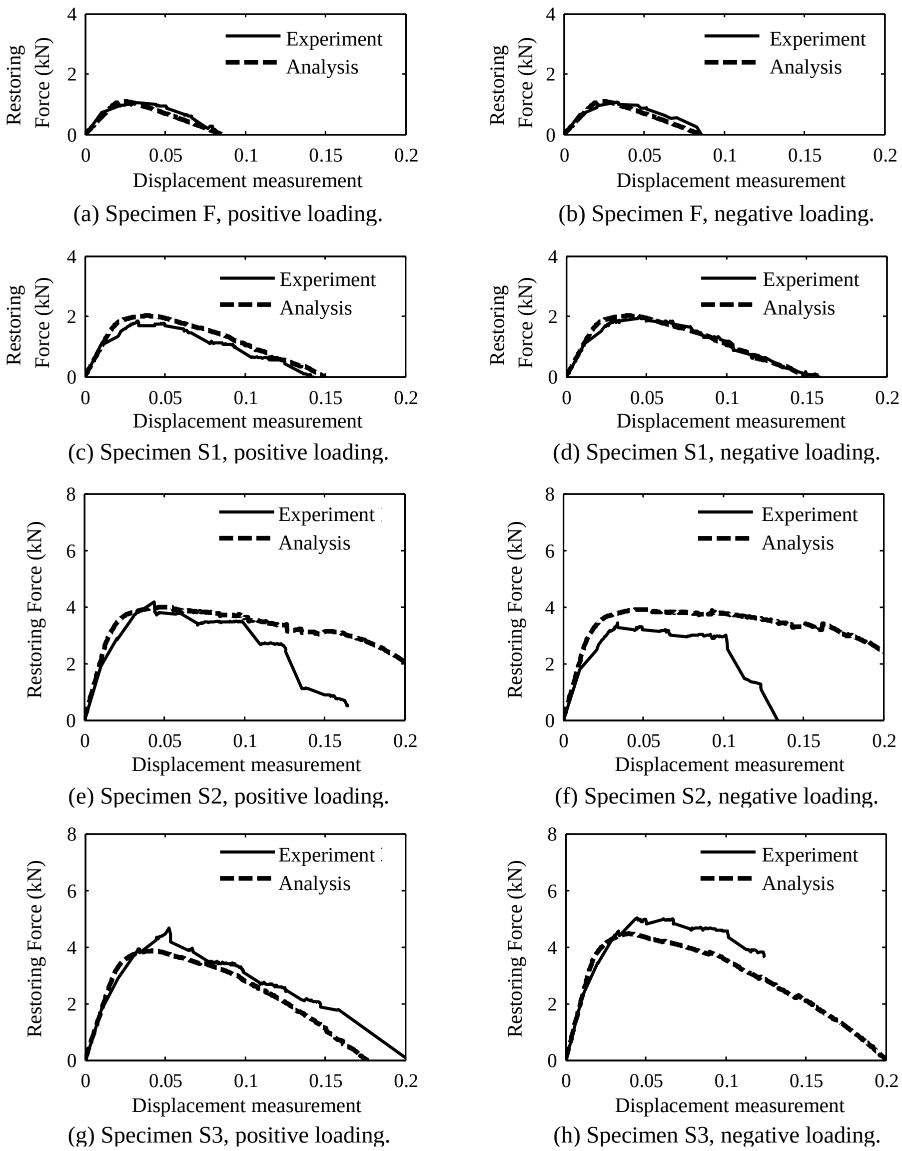


Figure 4. Simulation of skeleton curve on experimental result.

2.3 Modeling Procedure of Resistance on Joint

As an example of the procedure for modeling the resistance occurring at a column-beam joint in the positive direction, Figure 3 shows the compressive strain resistance on the side of the column.

a) In Figure 3(a), the nodes are determined on the columns and beams and are connected by beam elements.

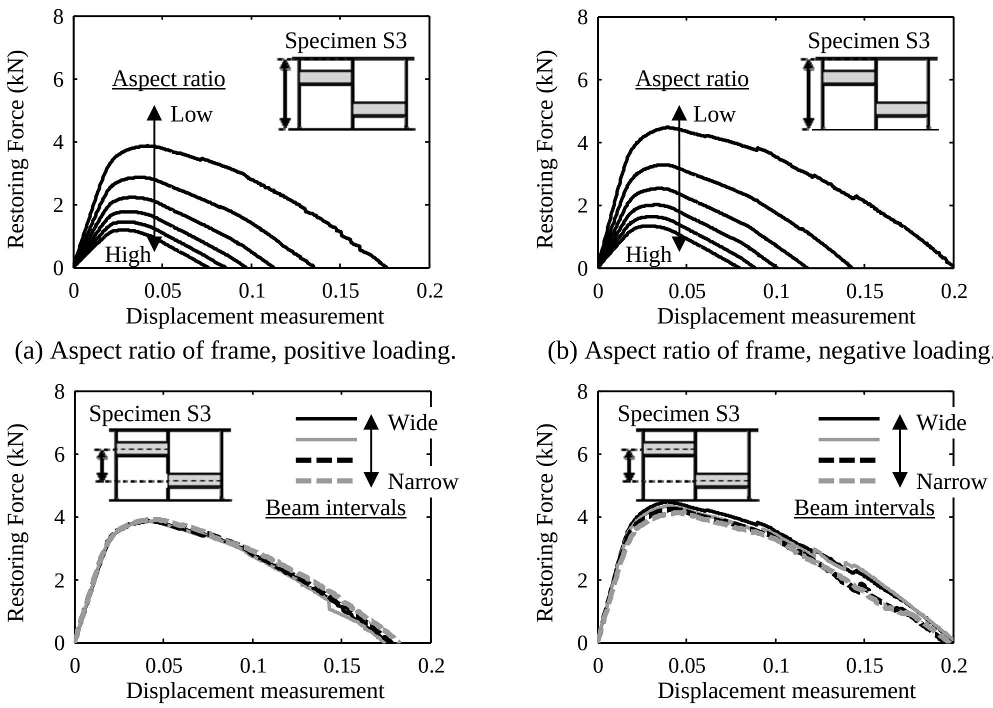
b) For a column, a rigid link is established from the column toward the point assumed to be subject to compressive strain; for a beam, the point-changing section of the member is shown in Figure 3(b).

c) In Figure 3(c), the nodes subject to compressive strain are connected by springs representing the compressive strain resistance.

d) When the joint moves, as shown in Figure 3(d), the compressive strain force is represented by the spring.

3 SIMULATED RESULT

Figure 4 compares the values of restoring force determined from the experiment and those from nonlinear analysis. The results of the analysis are almost equal to the test results for every specimen. Because it cannot check breaking member enough in program, the restoring force in negative loading is separated after 1/10 rad on specimen S2.



(a) Aspect ratio of frame, positive loading.
(b) Aspect ratio of frame, negative loading.
(c) Beam intervals, positive loading.
(d) Beam intervals, negative loading.

Figure 5. Sensitivity analysis of changing beam arrangement.

4 SENSITIVITY ANALYSIS OF BEAM ARRANGEMENT

We conducted a sensitivity analysis to study the effect of height arrangement of beams on the behavior of the whole frame. The results are shown in Figure 5. In the case of changed aspect ratio of frame for specimen S3, while keeping the beam height arrangement constant, it is observed that the restoring force decreases as the aspect ratio increases for both positive and negative loadings, as shown in Figure 5(a) and (b).

In the case of decreased interval of beam height arrangement for specimen S3, the restoring force increases a little in positive loading, but decreases a little in negative loading. In addition, the difference of restoring forces depends on the loading direction, as in Figure 5(c) and (d).

5 CONCLUSIONS

We simulated past cyclic loading tests on four traditional wooden frames with large-section beams to determine the seismic performance of the frames, while also studying the influence of the beams on the overall behavior of the frame. First, a simple analysis model of a fitting-type joint was constructed using beam elements. Next, this model was used to simulate the experimental results. Finally, a sensitivity analysis was conducted to study about the effect beam height arrangement on the behavior of the whole frame.

The major findings of this study were as follows:

a) Some material tests are conducted for wooden test pieces cut down from all columns of specimens. The compressive spring properties are decided.

b) Analysis models are constructed, and the restoring forces of frame specimens are simulated precisely. The results of the simulation showed that the restoring force values were almost equal to the experimental results.

c) The relation between height arranging beams and the change in restoring force is considered by sensitivity analysis.

Acknowledgments

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