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Bending resistance of repaired column members and shear resistance of opening frames with repaired columns of conventional Japanese wooden houses

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Abstract When it is necessary to repair conventional Japanese wooden houses, the decayed lower parts of columns should be replaced with new wood material. The bending resistance of columns repaired by four methods and the shear resistance of opening frames with those repaired columns were investigated in this study. Bending tests of the repaired columns showed differences in initial bending stiffness and maximum bending moment related to the repair methods and loading direction. Racking tests were conducted on door opening frames with conventional door head members or upper partial walls sheathed with 12-mm-thick plywood. The conventional frame specimens broke at door head–column joints with no obvious bending deformation of the columns, resulting in little difference in load–shear deformation curves among the repair methods. The columns of plywood-sheathed specimens, on the other hand, clearly were bent after the nails at the plywood-to-wood frame joints started to pull off. The load–shear deformation curves of the plywood-sheathed specimens did not vary regardless of the repair methods when shear deformations were small but were affected by repair methods as shear deformation increased.

Key words End-joint · Bending test · Racking test · Conventional frame · Plywood-sheathed frame

Introduction

The structural performance of timber constructions is degraded by some factors throughout their service periods.[1,2] Biological factors, wood fungi and termites particularly, bring about the risk of significant damage under high moisture conditions in timber construction. To recover the safety and serviceability of damaged construction, the deteriorated wood members should be removed and replaced with new wood materials.

Several studies have been reported on repair methods for deteriorated members in which mortise and tenon joints,[3] mechanical joints,[4,5] and adhesive joints[6–8] were examined.

However, practical data for the lateral resistance of repaired wooden frames of conventional Japanese wooden houses have not been accumulated sufficiently to provide a design basis for various repair methods. In repairing many conventional Japanese wooden houses, the lower parts of the columns often need to be replaced with new wood material because of the high probability of biological deterioration. This study focused on the bending resistance of columns repaired by four methods, which are called netsugi joints in Japanese, and the lateral resistance of opening frames with the repaired columns.

Materials and methods

Bending tests of wood members

Bending specimens were prepared from sugi (*Cryptomeria japonica*) with a cross section of 105 × 105 mm. The average wood density was 411 kg/m^3 (standard deviation, 34.9 kg/m^3), and average moisture content was 16.5% (standard deviation, 4.55%). Four point bending tests were conducted on the following specimens. The configurations of types B, C, D, and E are shown in Fig. 1.

Type A: Specimens without end-joint.
Type B: Specimens with glued-in hardwood dowels. Test members were end-jointed using four keyaki (*Zelkova*

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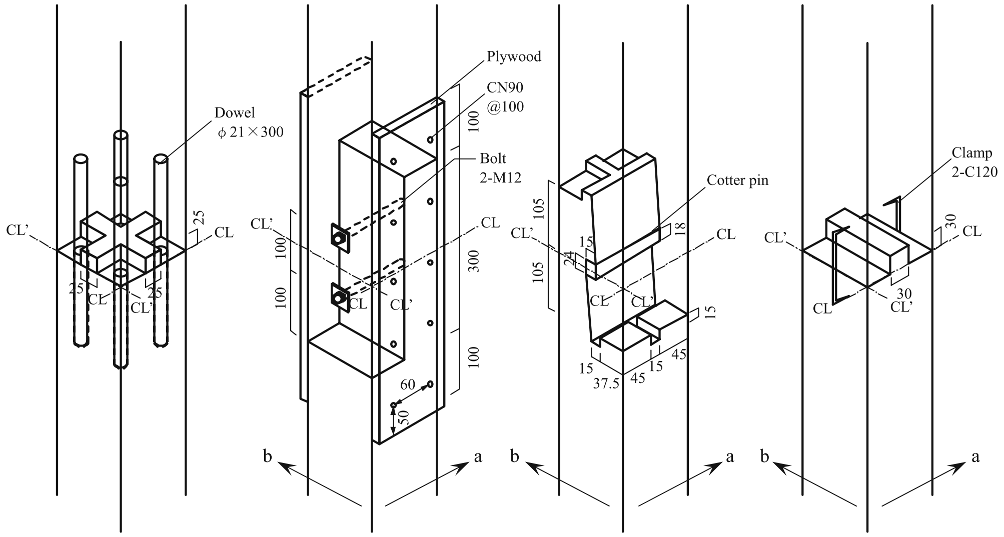


Type B

Loading direction a
Type Ca
Loading direction b
Type Cb

Loading direction a
Type Da
Loading direction b
Type Db

Loading direction a
Type Ea
Loading direction b
Type Eb

[Unit: mm]

Fig. 1. Longitudinal joints of repaired member. Line *CL–CL* or *CL′–CL′* denotes the center line of the bending span or the opening height of the wood frame

serrata) dowels with epoxy resin adhesive. The dowel was 21 mm in diameter and 300 mm in length; the lead hole of the member was 22 mm in diameter and 155 mm in depth.

Type C: Specimens end-jointed with 2 bolts and 20 nails. Bolt diameter was 12 mm. Column members and 12-mm-thick structural softwood plywood were connected with CN90. Type C was separated into types Ca and Cb according to loading direction.

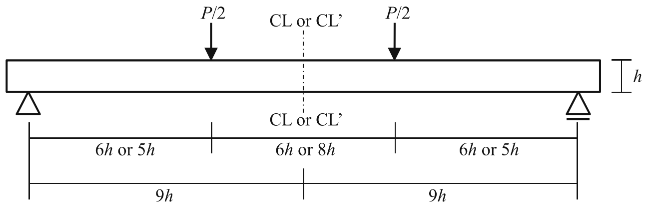
Type D: Specimens having the traditional Japanese tenon-mortise joint, called kanawatsugi. The cotter pin of this joint was keyaki. Type D was separated into types Da and Db according to loading direction.

Type E: Specimens end-jointed with two steel clamps (C120). The clamp was 6 mm in diameter, 45 mm in driven length, and 120 mm in length. Type E was separated into types Ea and Eb according to loading direction.

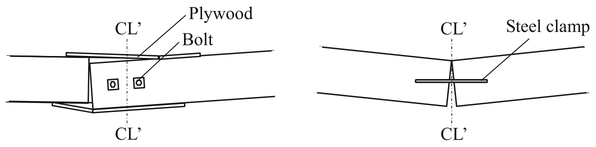
The bending tests were conducted on 6 specimens for each combination of joint type and loading direction, 48 specimens in total. The specimens were tested in four points of bending, with the bending span 18 times the specimen height (h), in which the distance between the loading points was $6h$ (types A, B, D, E) or $8h$ (type C) (Fig. 2a).

Bending deflection at the center of a specimen is generally measured in a bending test. However, measurement of the deflection may be difficult depending on the configuration of specimens with a repaired part because of sliding or opening at the end-joint (Fig. 2b,c). In this case, deflection of the specimen at two loading points was measured with two displacement transducers, and the bending angle of the specimen (Fig. 2d) was obtained from two measured deflections as follows:

$$\theta = \frac{2(\delta_1 + \delta_2)}{L - S} \tag{1}$$

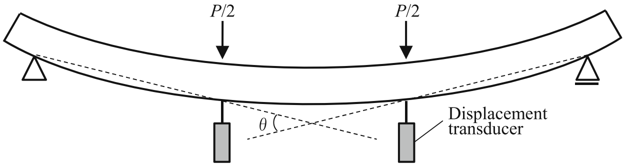


(a) Bending test condition



(b) Deformation of type Cb

(c) Deformation of type Eb



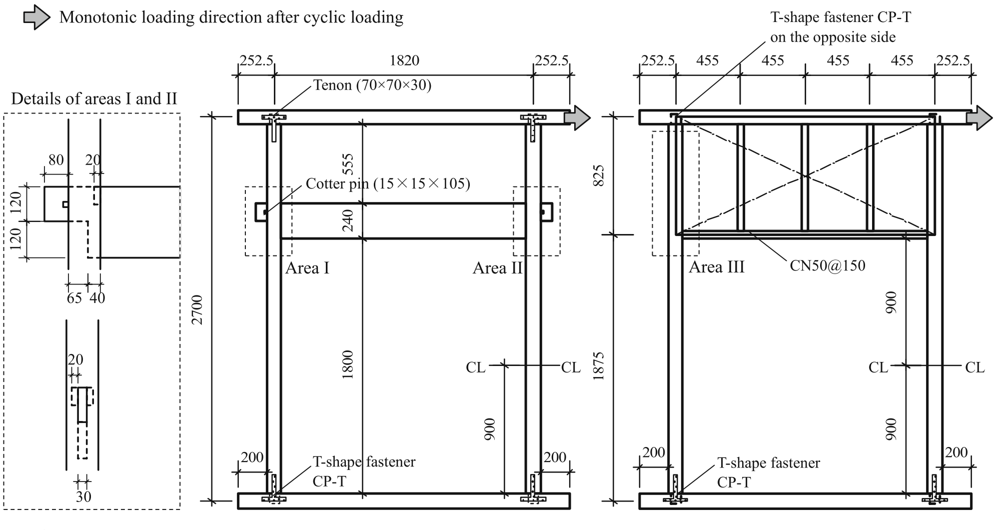
(d) Definition of bending angle

Fig. 2. Four points bending test. P, load; h, height of bending specimen; θ, bending angle; *line CL–CL* or *CL′–CL′* denotes the center line of the bending span

where θ is bending angle (rad), δ_1 and δ_2 are deflection (mm) measured by displacement transducers shown in Fig. 2d, L is bending span (mm), and S is the distance between the loading points (mm).

Racking tests of opening frames

Dimensions of frame specimens were 1,820 mm in length and 2,700 mm in height with an opening 1,800 mm in height (Fig. 3). The frame specimens consisted of 105 × 105 mm



[Unit: mm]

(a) Conventional wood frame specimen

(b) Plywood-sheathed specimen

Fig. 3. Configuration of wood frame specimen with opening. *Line CL–CL* denotes the repaired part

columns, a sill, and a beam of sugi solid lumber. Those members were connected with T-type steel plates (CP-T).

Racking tests were conducted on Japanese conventional door opening frames or upper partial walls sheathed with 12-mm-thick larch plywood. The conventional frames had door heads of 240 × 105 mm sugi. The door head and the columns were connected with 15 mm × 15 mm mizunara (*Quercus crispula*) cotter pins. The plywood-sheathed specimens had door heads of 45 × 105 mm sugi that were connected to the columns with four CN65 nails. The plywood was connected to the frame members with CN50 nails at 150-mm spacing.

The frame specimens had columns with or without end-joints (types A, B, Ca, Da, Ea: see Fig. 1). The repaired part was positioned at the center of the opening height. The racking tests were conducted on 3 specimens per each combination of frame type and joint type, 30 specimens in total.

Air-dried density and moisture content were obtained from the inside of the column member after racking tests. The average density of columns was 410 kg/m^3 (standard deviation, 46.7 kg/m^3). The moisture content of two columns was 93.2% and 51.5%, and the average moisture content of others was 16.3% (standard deviation, 3.63%); the effects of measured moisture content on shear resistance were not observed in this study. Moisture content of the repaired part may be lower than the foregoing values (93.2% and 51.5%) because the transverse section of the repaired member was exposed to room air.

A sill of the frame specimen was connected to a steel foundation with four bolts 16 mm in diameter. Two hold-down connections (BHU-20) were installed at the ends of the frame. The cyclic loading test step was repeated three times to produce 1/450, 1/300, 1/200, 1/150, 1/100, 1/75, and 1/50 rad of shear deformation. Then, the frame specimens were loaded monotonically until shear deformation was more than 1/15 rad.[9]

Results and discussion

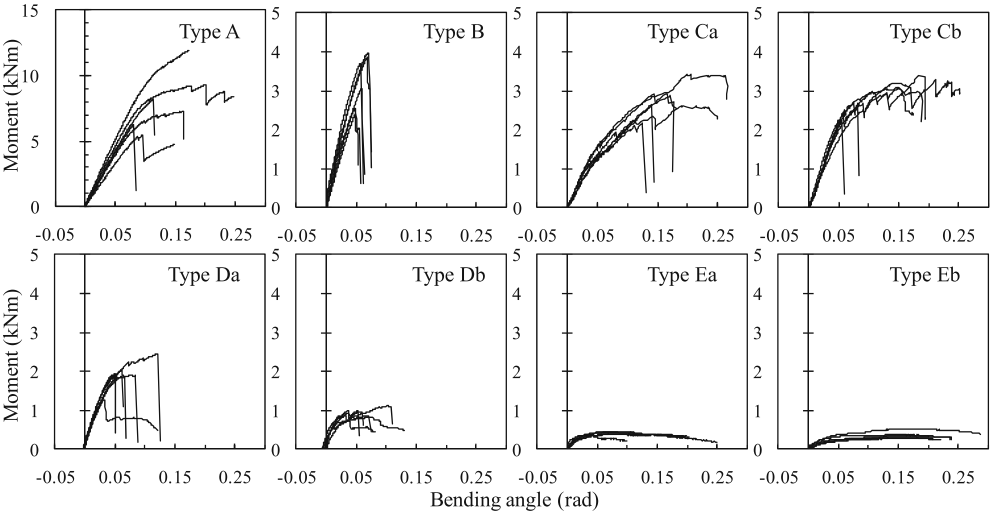
Difference in bending resistance among repair methods

Figure 4 shows bending moment–bending angle curves obtained from the bending tests. The shapes of the bending moment–bending angle curves varied clearly according to joint type. The bending moment of type A was increased up to 5.5–11.9 kNm, but the maximum bending moment of other types was less than 4 kNm. Initial bending stiffness and maximum bending moment were obtained from the moment–bending angle curves. Initial bending stiffness was defined as the line that passes through points on the curves corresponding to 10% and 40% of the maximum bending moment.

Figure 5 shows the initial bending stiffness and the maximum bending moment of each joint type. The initial bending stiffness differed noticeably depending on joint type and loading direction. Type B showed the highest initial bending stiffness of those repair methods, and its initial bending stiffness was 77% of the control specimen (type A) on average. Type Eb showed the lowest values; its initial bending stiffness was 12% of the control specimen in average. A difference in the initial bending stiffness of joint types Ca and Cb was observed as a result of loading direction, and that of type Ca was 68% of that of type Cb. However, in the other types the effect of loading direction on the initial bending stiffness was not clear because types Db and Ea had a large standard deviation.

The maximum bending moments of the repaired member on each joint type had a small standard deviation and were 4.6% to 40% of the control specimen on average. The maximum bending moment differed with the combination of joint type and loading direction. The maximum bending moment of types Ca and Ea were similar to that of types

Fig. 4. Bending moment–bending angle curves



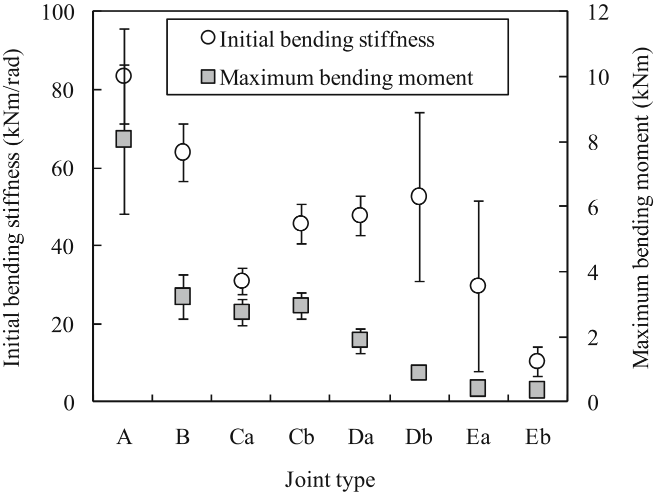


Fig. 5. Initial bending stiffness and maximum bending moment on each joint types. *Symbols* and *bars* indicate mean value and standard deviation, respectively

Cb and Eb, and the former were 94% and 114%, respectively, of the latter. In contrast, the maximum bending moment of type Da showed a value about two times higher than that of type Db.

Difference in shear resistance of opening frames among repair methods

The conventional frame specimens broke at the tenon of the door head member or at the cotter pin of the door head–column joints (areas I or II: see Fig. 3); however, bending deformation of the repaired column obviously was not observed until the racking test terminated. Figure 6 shows the envelope load–deformation curves obtained from the racking tests of conventional frame specimens. The specimens that broke by tension fracture or plug shear at the tenon of the door head member showed low load (some specimens of types Ca, Da, and Ea). The load–deformation curves of specimens that broke by partial compression at the cotter pin or split at the tenon of the door head were little affected by the repair methods, and those loads were gradually increased up to nearly 1/10 rad.

The columns of plywood-sheathed specimens were bent clearly after the nails at the plywood-to-wood joints started to pull off (see area III in Fig. 3). Figure 7 shows the envelope load–deformation curves obtained from the racking tests of plywood-sheathed specimens. Types A and B showed similar load–deformation curves, whose load increased up to nearly 1/10 rad even though the load decreased once the nails pulled off the frame member. The load of types Ca and Da also increased after nails were pulled from the frame member, but those loads showed smaller increase than in types A and B because the repaired part suffered noticeable damage. Type Ea showed characteristic load–deformation curves in which the load was almost constant after 1/17 rad and later. The load–deformation curves of plywood-sheathed specimens were affected by the repair methods.

Load at 1/120 rad, yield load, ultimate load, and maximum load were calculated from the load–deformation curves up to 1/15 rad according to the evaluation method of allowable shear resistance for shear walls.[9] Table 1 shows mean values of the results obtained from the racking tests.

For some of the conventional frame specimens, their yield loads and/or ultimate loads could not be calculated. Because the load of load–deformation curves of those specimens was approximately straight as they increased up to maximum load, those load–deformation curves could not be adequately replaced with a perfect elastic-plastic model defined by the standard evaluation method.[9] The loads at 1/120 rad of types A, B, Ca, Da, and Ea were 0.47, 0.81, 0.52, 0.60, and 0.70, respectively; there were differences among specimen types. However, this difference may be caused by the degree of fixation between door head–column joints because little damage was observed in the repaired part until the racking test terminated. The maximum load of types B, Ca, Da, and Ea was 92% to 109% of type A on average, and the differences between the former and the latter were not significant at the 95% confidence level.

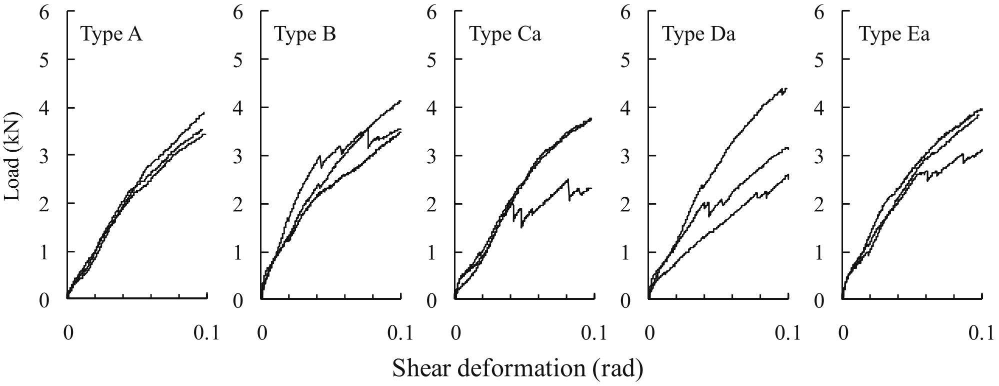


Fig. 6. Envelope load–deformation curves of conventional frame specimens

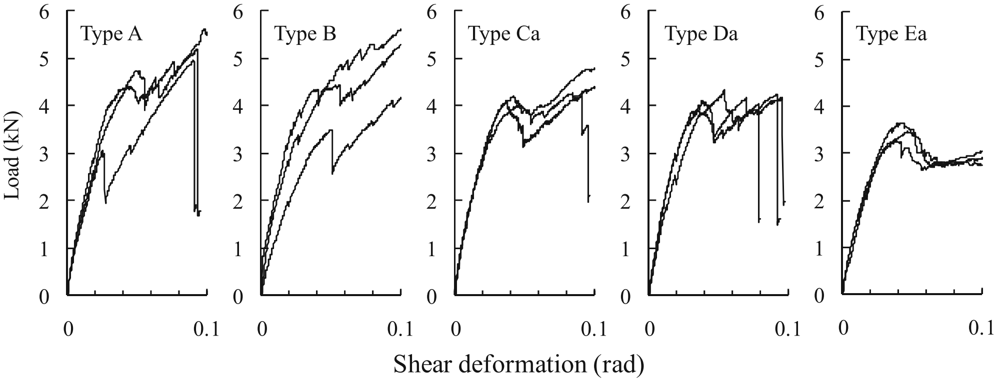


Fig. 7. Envelope load–deformation curves of plywood-sheathed specimens

Table 1. Results of racking tests

Specimen	P_{120} (kN)	P_y (kN)	D_y (rad)	P_u (kN)	D_u (rad)	P_{max} (kN)	D_{max} (rad)	U_{15} (kN·rad)
Conventional frame specimen								
Type A	0.47	2.40	0.054	–	–	2.85	0.067	0.106
Type B	0.81	1.99	0.029	2.94	0.067	3.09	0.067	0.131
Type Ca	0.52	–	–	–	–	2.76	0.067	0.104
Type Da	0.60	1.42	0.031	1.97	0.067	2.61	0.067	0.102
Type Ea	0.70	1.68	0.026	2.68	0.067	2.99	0.064	0.120
Plywood-sheathed specimen								
Type A	1.44	2.76	0.020	3.98	0.067	4.44	0.061	0.208
Type B	1.50	2.10	0.014	3.49	0.067	3.91	0.060	0.189
Type Ca	1.55	2.19	0.013	3.84	0.067	4.12	0.041	0.213
Type Da	1.50	2.33	0.015	3.78	0.067	4.17	0.053	0.207
Type Ea	1.29	1.95	0.015	3.16	0.067	3.47	0.042	0.174

P_{120}, load at 1/120 rad; P_y, yield load; D_y, yield deformation; P_u, ultimate load; D_u, ultimate deformation; P_{max}, maximum load up to 1/15 rad; D_{max}, deformation at maximum load; U_{15}, energy capacity up to 1/15 rad

–, characteristic values could not be calculated on three specimens

In the plywood-sheathed specimen, the load at 1/120 rad of types B, Ca, Da, and Ea was 90% to 107% of type A on average; the differences between the former and the latter were not significant at the 95% confidence level. The maximum loads of types B, Ca, Da, and Ea were 88%, 93%, 94%, and 78% of type A on average, respectively, and only the difference between types A and Ea was significant at the 95% confidence level.

Conclusions

Bending tests and racking tests were conducted on column members repaired by four methods and the opening frames with those repaired columns, respectively. The obtained results can be summarized as follows:

1. Initial bending stiffness and maximum bending moment of a repaired column member are noticeably affected by a combination of repair method and loading direction.
2. Although the bending resistance of the column member is largely changed by the repair method, the shear resistance of conventional frames with a repaired column is little affected by repair methods.
3. The shear resistance of plywood-sheathed frames with a repaired column is little affected by the repair method when shear deformations are small but is affected by repair method as shear deformation increases.

4. The shear resistance of opening frames with a repaired column is dependent on the combination of frame and repair method.

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