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

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Keywords: End-joint, Bending test, Racking test, Conventional frame, Plywood-sheathed frame

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Abstract

In many cases of repairing Japanese conventional wooden houses, decayed lower parts of columns should be replaced with new wood material. Bending resistance of columns repaired by four methods and 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 among the combinations of repair methods and loading directions. Racking tests were conducted on door opening frames with conventional door head member or upper partial walls sheathed with 12mm thick plywood. The conventional frame specimens broke at door head-column joints with no obvious bending deformation of the columns, it resulted in little difference in load-shear deformation curves among the repair methods. The columns of plywood-sheathed specimens, on the other hand, were bent clearly after when the nails at the plywood to wood frame joints started to be pulled off. The load-shear deformation curves of the plywood-sheathed specimens did not vary regardless of the repair methods in small shear deformations, but affected by the repair methods as shear deformations increased.

Keywords

End-joint, Bending test, Racking test, Conventional wood frame, Plywood-sheathed frame

Introduction

Structural performance of timber constructions is degraded by some factors throughout their service periods[1-2]. Biological factors, wood fungi and termite, particularly bring about the timber constructions the risk of significant damages under high moisture condition. To recover the safety and serviceability of damaged constructions, deteriorated wood members should be removed and replaced with new wood materials.

Several studies have been reported on repair method for deteriorated members up to the present, in which mortise and tenon joints[3], mechanical joints[4-5] and adhesive joints[6-8] were examined.

However, practical data of the lateral resistance of repaired wooden frames of Japanese conventional wooden houses have not been accumulated enough to prepare design basis for various repair methods at present. In many cases of repairing Japanese conventional wooden houses, lower parts of columns often need to be replaced with new wood material because of high probability of biological deterioration. This study focused on bending resistance of columns repaired by four methods, which were called as netsugi joint in Japanese, and 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 cross section of 105mm x 105mm. The average wood density was 411kg/m^3 (standard deviation, 34.9kg/m^3) and the average moisture content was 16.5% (standard deviation, 4.55%). Four points bending tests were conducted on the following specimens. Configuration 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 4 keyaki (*Zelkova serrata*) dowels with epoxy resin adhesive. The dowel was 21mm in diameter and 300mm in length and lead hole of the member was 22mm in diameter and 155mm in depth.

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

Type D: specimens having Japanese traditional tenon-mortise joint called for kanawatsugi. Cotter pin of this joint was keyaki. Type D was separated types Da and Db according to loading direction.

Type E: specimens end-jointed with 2 steel clamps (C120). The clamp was 6mm in diameter, 45mm in driven length and 120mm in length. Type E was separated types Ea and Eb according to loading direction.

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

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

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

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

Racking tests of opening frames

Dimensions of frame specimens were 1820mm length and 2700mm height with an opening 1800mm in height shown in Fig. 3. The frame specimens consisted of 105mm x 105mm 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 12mm thick larch plywood. The conventional frames had 240mm x 105mm sugi door head. The door head and the columns were connected with 15mm x 15mm mizunara (*Quercus crispula*) cotter pin. The plywood-sheathed specimens had 45mm x 105mm sugi door head that was connected to the columns with four CN65 nails. The plywood was connected to the frame members with CN50 nails at 150mm spacing.

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

Air-dried density and moisture content were obtained from the inside of column member after racking tests. The average density of columns was 410kg/m^3 (standard deviation, 46.7kg/m^3). The moisture content of 2 columns was 93.2% and 51.5% and the other average moisture content was 16.3% (standard deviation, 3.63%), provided that the effects of measured moisture content for shear resistance were not observed in this study. Moisture content of the repaired part may be low than above values (93.2% and 51.5%) because the transverse section of repaired member was exposed to room air.

A sill of frame specimen was connected to steel foundation with 4 bolts of 16mm diameter. Two hold-down connections (BHU-20) were installed at ends of the frame. Step of the cyclic loading test was repeated three times to produce 1/450, 1/300, 1/200, 1/150, 1/100, 1/75 and 1/50rad of shear deformation. And then the frame specimens were loaded monotonically until shear deformation was more than 1/15rad[9].

Results and discussion

Difference in bending resistance among repair methods

Fig. 4 shows bending moment-bending angle curves obtained from bending tests. Shapes of bending moment-bending angle curves varied clearly according to joint types. The bending moment of type A was increased up to 5.5-11.9kNm, but the maximum bending moment of other types were less than 4kNm. 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.

Fig. 5 shows the initial bending stiffness and the maximum bending moment of each joint type. The initial bending stiffness differed noticeably depending on joint types and loading directions. 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) in average. Type Eb showed the lowest values and its initial bending stiffness was 12% of the control specimen in average. The initial bending stiffness of joint types Ca and Cb was observed difference due to loading direction, and that of type Ca was 68% of that of type Cb. However, the other was not clear the effect of loading direction on the initial bending stiffness because types Db and Ea had large standard deviation.

The maximum bending moments of the repaired member on each joint type had small standard deviation, and were 4.6% to 40% of the control specimen in 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 Cb and Eb, and the former were 94 % and 114% of the latter, respectively. In contrast, the maximum bending moment of type Da showed about two times higher value than type Db.

Difference in shear resistance of opening frames among repair methods

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

The columns of plywood-sheathed specimens were bent clearly after when the nails at the plywood to wood joints started to be pulled off at area III in Fig. 3. Fig. 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 near 1/10rad even though once load decreased by pulling off of nails from frame member. The load of types Ca and Da also increased after nails were pulled off from frame member, but those loads showed small increase than the case of types A and B because the repaired part suffered noticeably damage. Type Ea showed characteristic load-deformation curves which the load was almost constant after 1/17rad and later. The load-deformation curves of plywood-sheathed specimens were affected by the repair methods.

Load at 1/120rad, yield load, ultimate load and maximum load were calculated from the load-deformation curves up to 1/15rad 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.

Some of the conventional frame specimens could not be calculated their yield loads and/or ultimate loads. Because the load of load-deformation curves of those was approximately straight increased up to maximum load, those load-deformation curves could not be adequately replaced with perfect elastic-plastic model defined by the standard evaluation method[9]. The load at 1/120rad of types A, B, Ca, Da and Ea were

0.47, 0.81, 0.52, 0.60 and 0.70, respectively, there are differences among specimen types. But this difference may be caused by the degree of fixation between door head-column joints because damage was little observed in the repaired part until racking test terminated. The maximum load of types B, Ca, Da and Ea were 92% to 109% of type A in average, and the differences between the former and the latter were not significant at 95% confidence level.

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

Conclusions

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

1. Initial bending stiffness and maximum bending moment of repaired column member are noticeably affected by combination of repair methods and loading directions.
2. Although the bending resistance of column member is largely changed by the repair methods, the shear resistance of conventional frames with repaired column is little affected by the repair methods.
3. The shear resistance of plywood-sheathed frames with repaired column is little affected by the repair methods in small shear deformation, but is affected by the repair methods as shear deformation increase.
4. The shear resistance of opening frames with repaired column is dependent on combination of

configuration of frame and repair method.

Acknowledgements

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Title figures

Fig. 1. Longitudinal joints of repaired member.

Line CL-CL or CL’-CL’ denote the center line of bending span or opening height of wood frame.

Fig. 2. Four points bending test.

P, load; *h*, height of bending specimen; θ, bending angle; line CL-CL or CL’-CL’ denote the center line of bending span.

Fig. 3. Configuration of wood frame specimen with opening.

Line CL-CL denotes the repaired part.

Fig. 4. Bending moment-bending angle curves.

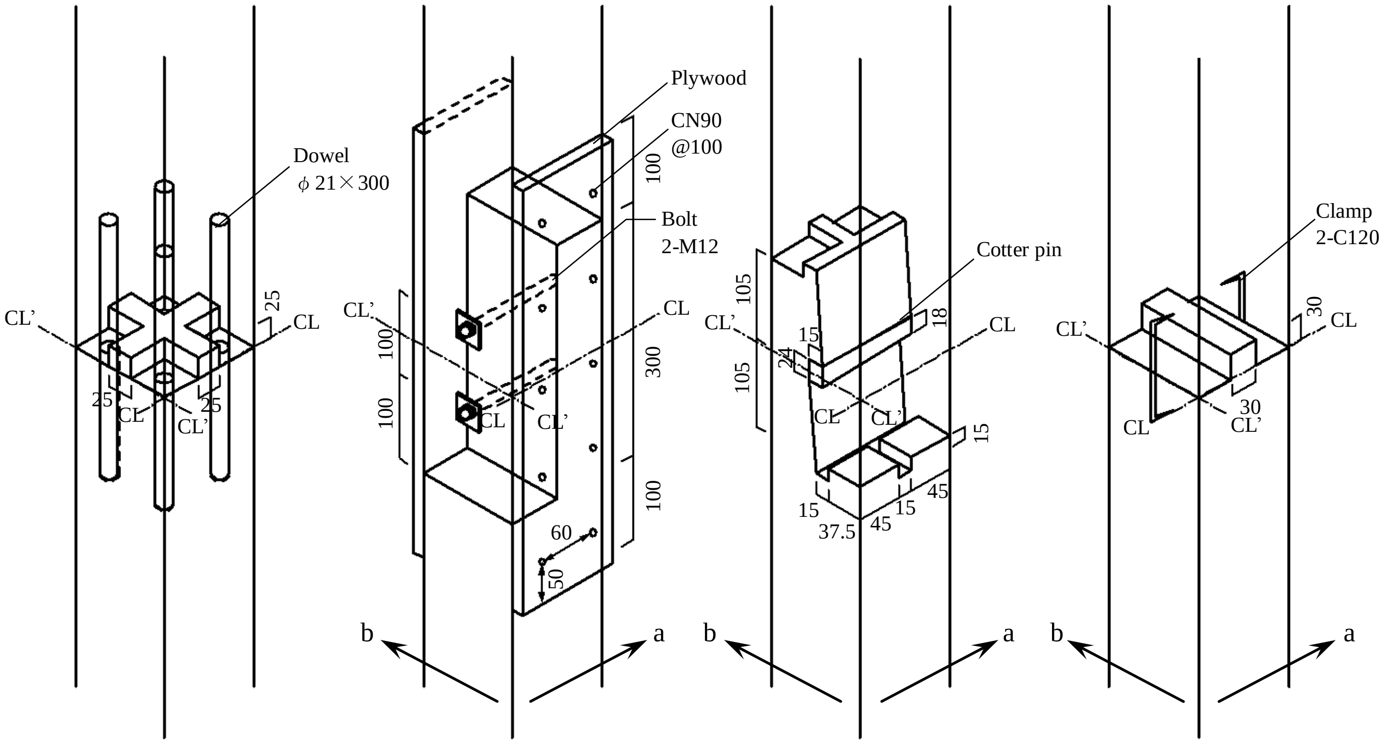
Fig. 5. Initial bending stiffness and maximum bending moment on each joint types.

Symbols and bars indicate mean value and standard deviation, respectively.

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

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

Fig. 1.



Type B

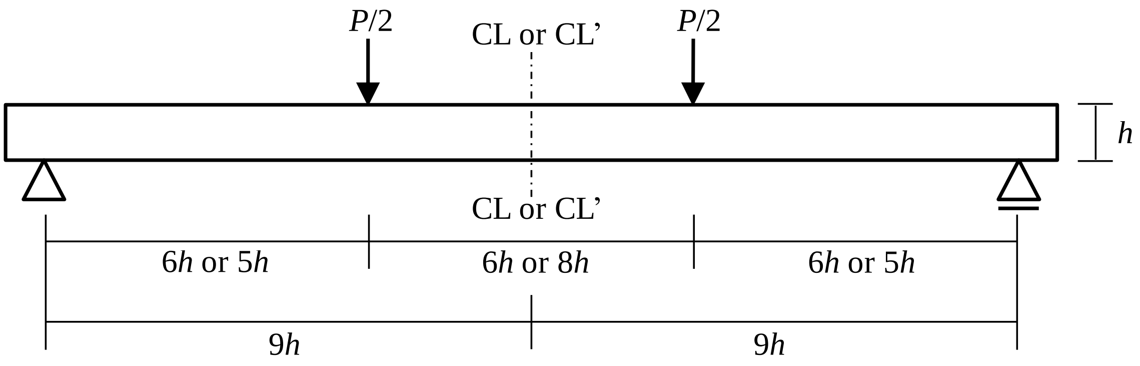
[Unit: mm]

Loading direction a
Type Ca
Loading direction b
Type Cb

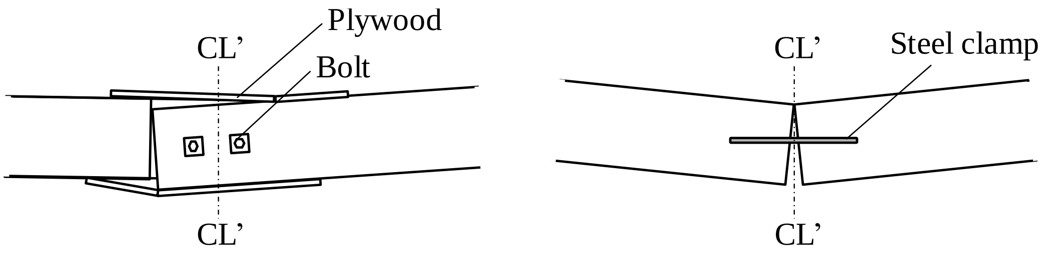
Loading direction a
Type Da
Loading direction b
Type Db

Loading direction a
Type Ea
Loading direction b
Type Eb

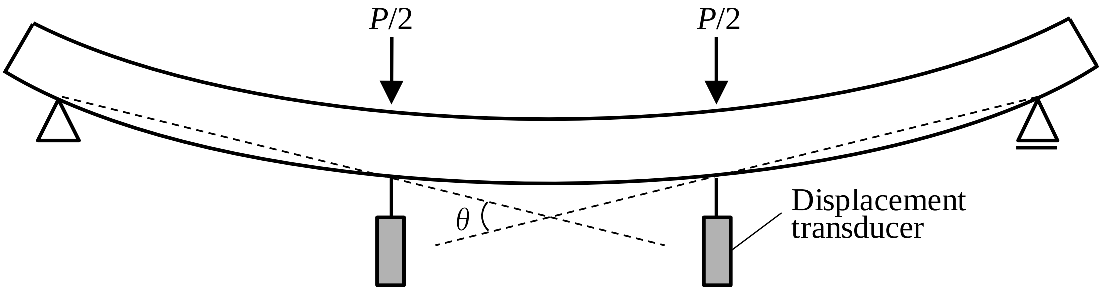
Fig. 2.



(a) Bending test condition

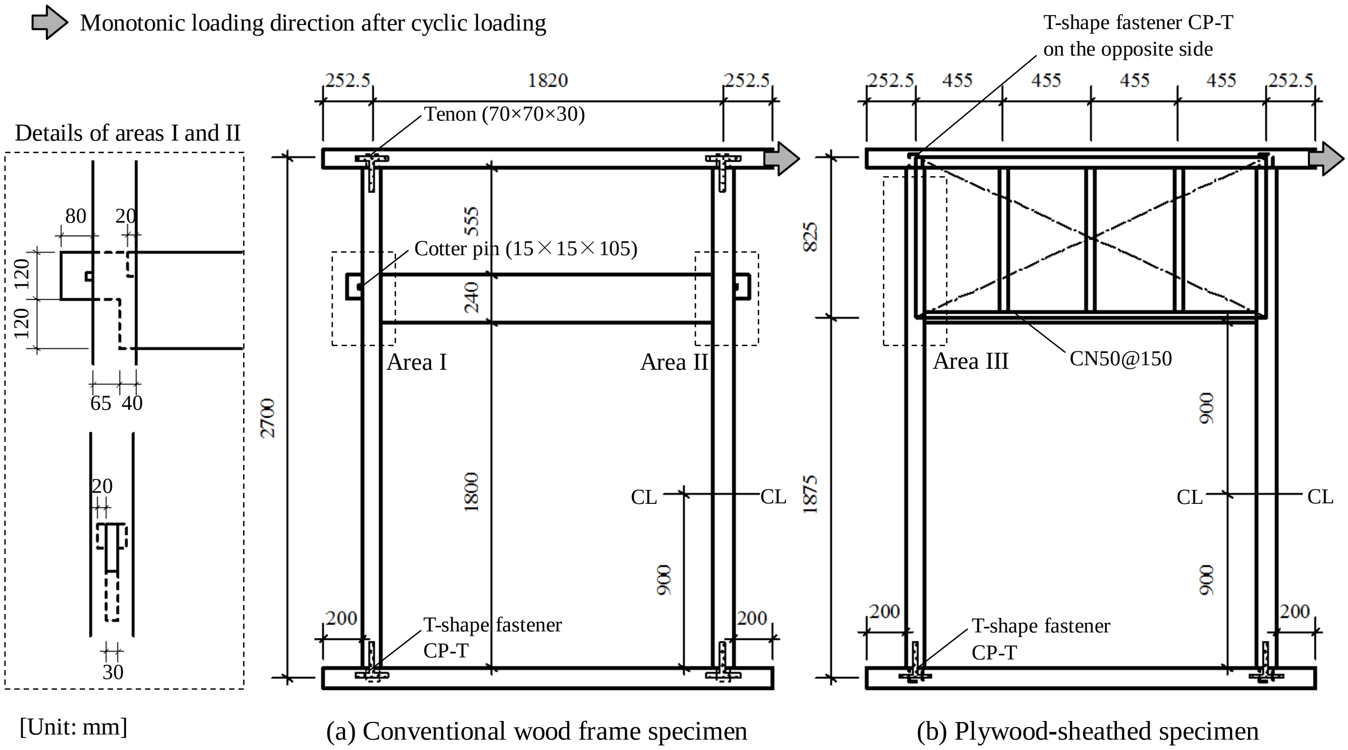


(b) Deformation of type Cb (c) Deformation of type Eb



(d) Definition of bending angle

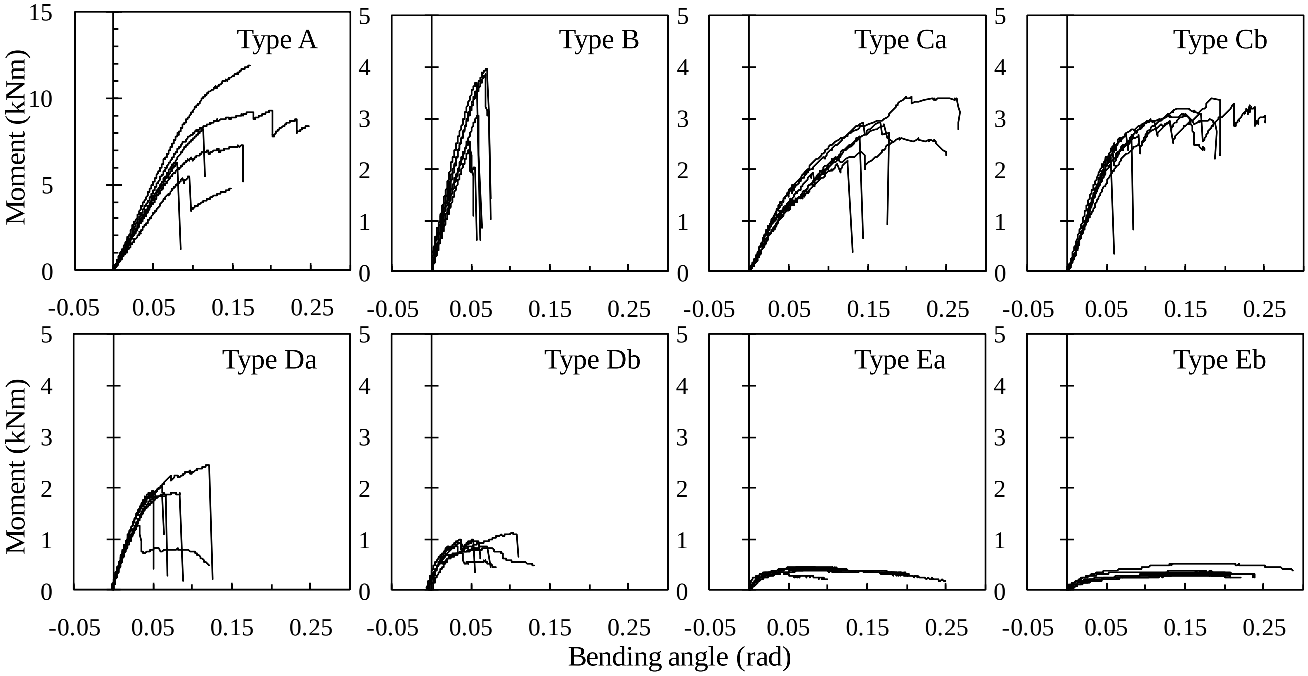
Fig. 3.



(a) Conventional wood frame specimen

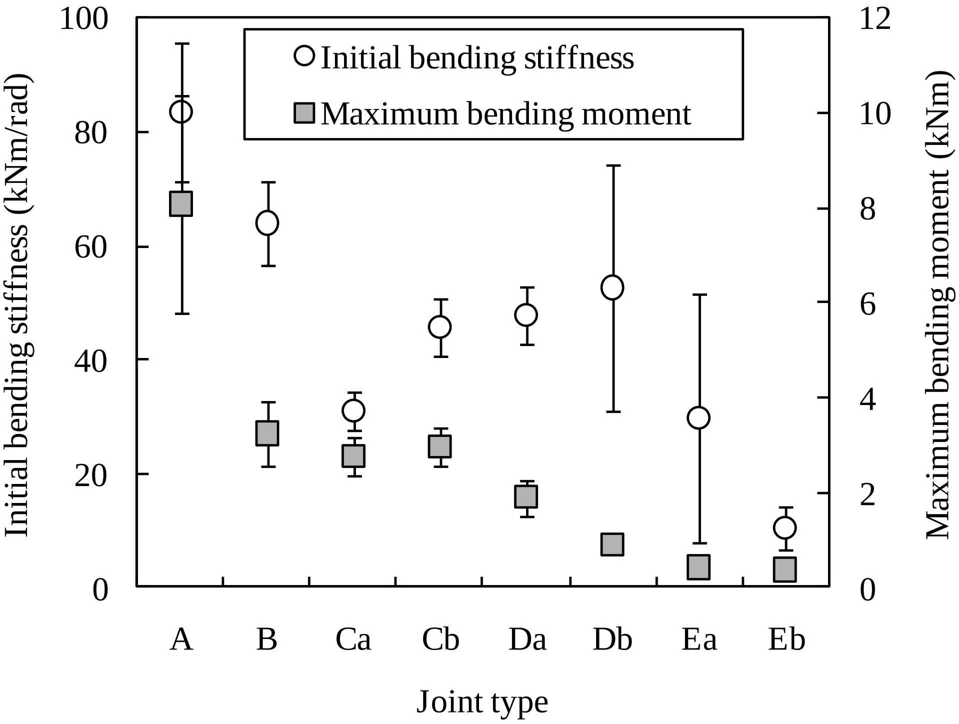
(b) Plywood-sheathed specimen

Fig. 4.



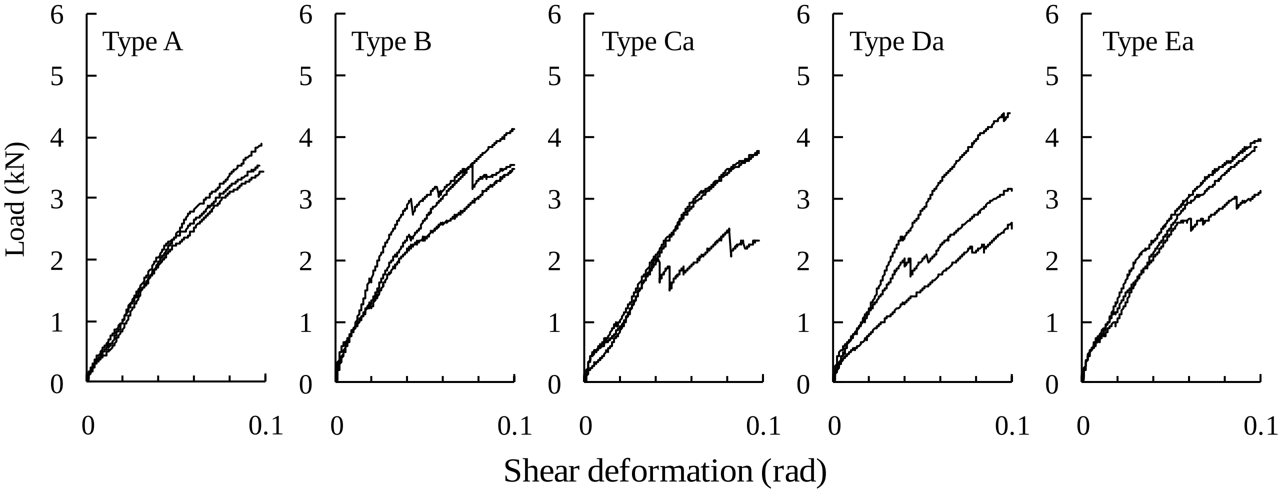
Type A
Type B
Type Ca
Type Cb
Type Da
Type Db
Type Ea
Type Eb
Moment (kNm)
Moment (kNm)
Bending angle (rad)
15
10
5
0
4
3
2
1
-0.05
0.05
0.15
0.25

Fig. 5.



Initial bending stiffness (kNm/rad)
100
80
60
40
20
0
Maximum bending moment (kNm)
12
10
8
6
4
2
0
○ Initial bending stiffness
■ Maximum bending moment
A
B
Ca
Cb
Da
Db
Ea
Eb
Joint type

Fig. 6.



Type A
Type B
Type Ca
Type Da
Type Ea
Load (kN)
0
1
2
3
4
5
6
0
0.1
Shear deformation (rad)

Fig. 7.

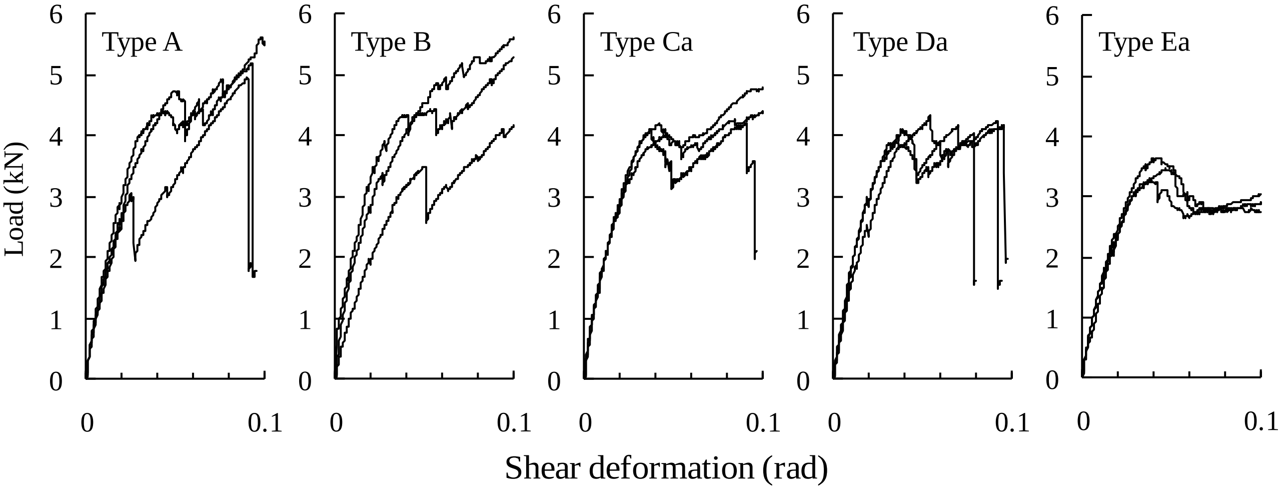

Type A
Type B
Type Ca
Type Da
Type Ea
Load (kN)
0
1
2
3
4
5
6
0
0.1
Shear deformation (rad)

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 tp 1/15 rad; D_{max}, deformation at maximum load; U_{15}, energy capacity up tp 1/15 rad; - indicates that characteristic values could not be calculated on three specimens