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Experimental study on flexural properties of timber columns with interior notches in traditional Japanese timber structures

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Abstract

In this study, the columns with interior notches in traditional Japanese timber frames were selected as the research object, and static bending tests were performed to investigate the effect of interior notches on the flexural properties of columns. First, the bending behaviors of columns under three-point and four-point load configurations were compared to obtain a suitable referenced strength of a column without notches. The reduction in the load-bearing capacity of columns with different types of interior notches in traditional Japanese timber structures was determined through experimental tests and statistical analysis. The results indicated that the mean bending strength of columns with three different notch types was consistent with those without notches, the continuous timber on both sides of the notch had a beneficial effect on maintaining a higher strength and reducing the stress intensity around the notch. The fracture position and the standard deviation of the bending strength were affected not only by the notch depth, but also by the notch width on the tensile side of the column.

Keywords: Traditional timber frame, Bending strength, Interior notch, Load configuration, Wood column

Introduction

In evaluating the lateral resistance of traditional Japanese timber structures consisting of large dimensional beams, columns, and hanging walls, the performance of the main structural elements should be assessed in addition to the evaluation of shear walls. Based on quasi-static tests on a frame with deep beams and hanging mud walls [1], it was observed that the bending behavior of columns, moment resistance of the tenon–mortise joints and shear resistance of the hanging walls contributed to the lateral resistance of the entire frame. Considering that the forces generated on the joints, beams, and hanging walls are transmitted to the columns, the damage limit of the columns directly affects the load-bearing capacity of the

entire structure. In this study, the bending performance of columns in a traditional timber frame was investigated.

The load-bearing capacity of a bending member is generally estimated as the product of the effective section modulus and the characteristic bending strength [2]. The characteristic strength is normally determined through four-point (4P) bending tests [3, 4] considering the scale factor. In terms of traditional timber columns, the concentrated force is transferred from the beam end to the column and subjected to three-point (3P) bending. According to the evaluation of the load configuration effect based on the Weibull theory [5], the load-bearing capacity of a beam subjected to midspan 3P bending is approximately 1.21 that of 4P bending, and influenced by the stressed volume difference. Although the flexural strength under 3P bending is higher than that of 4P bending based on many experimental results [6, 7], the difference in the rates of increase between 3 and 4P load configurations varies, depending on the material.

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In traditional timber structures, the columns and beams are typically connected using mortise–tenon joints; consequently, interior notches are required on the columns. The abrupt change in the cross-section owing to the notch is likely to cause stress concentration and brittle failures of the bending member, significantly reducing the load-bearing capacity. Thus, the notch should be avoided or permitted based on strict restrictions in the size and location in several standards [2, 8, 9]. The relevant estimations are also based on the analysis of the stress concentration effect at the sharp interior corner of the notch on the flexural strength. Ashby et al. [10] determined the fracture energy of a notched beam based on the crack propagation mechanism. Murphy [11, 12] simplified the large notches on a beam as slits and developed an estimation method based on stress intensity factors. A conservative crack-initiation criterion for beams with notches and slits for most softwood species is presented in the FPL wood handbook [13]. The interior notch in the above standards and studies is a general condition in which the notch penetrates the tensile side of the beam in the width direction. The height and the length ratios of the notch are mainly considered to be correlated to the flexural properties. In the case of a notch opened for the traditional tenon–mortise joint on the column, only a part of the section is cut in the width direction, and the width and depth of the notch are changeable at different positions of one joint. A combination of notches in different directions of the column may also exist (Fig. 1), which makes it challenging to analyze the flexural behavior of the column using current design methods. Shoji et al. [14] evaluated the effects of directions and the length ratio of the partial section loss on the columns and proposed a simplified bending rigidity

model. The fundamental data for estimating the bending strength reduction in columns with interior notches in traditional timber frames are still limited.

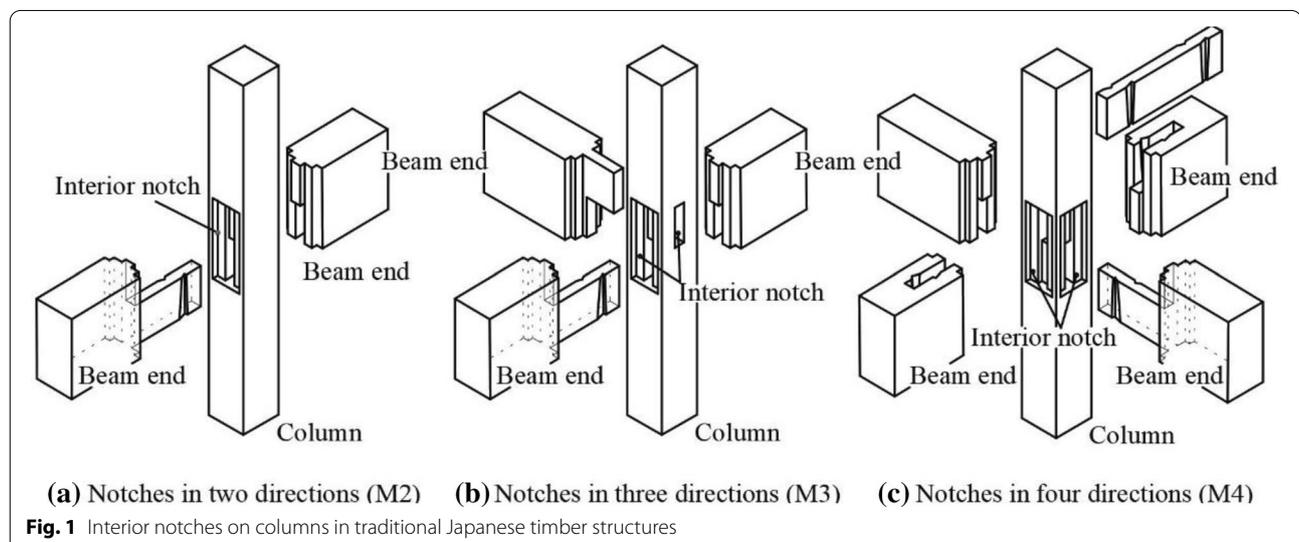
The aim of this study is to investigate the load-bearing capacity of a traditional timber column for practical design, considering the possible increase caused by the load configuration effect and the possible decrease caused by the interior notches. Based on two widely used tree species and timber section sizes adopted in Japan, the flexural properties of columns without notches under 3P and 4P load configurations and columns with three different notch combinations in multiple directions were analyzed experimentally and statistically.

Materials and methods

Two series of experimental bending tests were conducted. In the first series, static tests under two load configurations were performed: 3P and 4P bending tests with a span-to-depth ratio of 18. In the second series, three types of notch combinations were set at the loading point through 3P bending tests and compared with the case without notches.

3P and 4P bending tests

The materials used in this study were Japanese cypress (*Chamaecyparis obtusa*) and Japanese cedar (*Cryptomeria japonica*), both of which are widely used as columns of traditional Japanese timber frames. During the construction of traditional buildings, the selection of column materials often depends on a visual assessment by carpenters, particularly for the materials with fewer defects around the opening. Air-dried sawn timber with drying splits and a few defects, cultivated in Yoshino, Nara Prefecture, Japan, was used for constructing the



specimens. The bending specimen cross-sections were 150 mm × 150 mm and 180 mm × 180 mm, which generally satisfy the bending requirement of independent columns. Sixteen specimens were prepared for each tree species, section size, and load configurations to satisfy the reliability of the statistical values. The dynamic modulus of elasticity in the tangential flexural vibration (E_f) of each specimen was measured before static bending. Both the Japanese cypress and Japanese cedar specimens met the standard elastic modulus requirement of the upper class defined in the JAS standard [15].

The schematic and specifications of the simply supported specimens with a span-to-depth ratio of 18 for the bending tests are shown in Fig. 2 and Table 1, respectively. For the 3P bending test, the distance between a concentrated loading point and the support was $1/3L$; for the 4P bending test, two equal concentrated loads with the distance of $1/3L$ were placed equidistant between the supports. The crosshead speed was controlled at 8 mm/

min, and the deflection was measured using displacement transducers placed at the load and support points. The names of the test specimens included details about the tree species (S for Japanese cedar and H for Japanese cypress), section size (15 for a section size of 150 mm and 18 for a section size of 180 mm), and load configuration (3P and 4P bending).

3P bending tests with and without interior notches

The materials used for bending specimens with interior notches were homogeneous glued laminated timber composed of Japanese cypress with a strength class of E95-F315 and Japanese cedar with a strength class of E55-F225, as defined in the JAS standard [16]. In order to compare the effect of interior notch on the flexural characteristics of the columns, the 3P bending test was designed to be performed twice on each specimen to measure the bending performance of columns in the conditions with and without notches. The total length of the specimen was 5.3 m, and the bending test span was 3 m. The designed outer laminate on the tensile side was 4 m long without any finger joints to maintain consistency in the strength of outer laminate within the range of the stress concentration area for the two-bending tests with and without notches. A schematic and specifications of the test specimens are presented in Fig. 3 and Table 2, respectively. In addition to different tree species, the test variables included two sectional dimensions (150 mm × 150 mm, and 180 mm × 180 mm) and three types of notches along the loading point (M2, M3, and M4). The three notches to mortise forms when the deep beams are inserted into the column from two, three, and four directions in practice. The schematic and corresponding dimensions of the different notch types are shown in Fig. 4 and Table 3, respectively. Because the width of notches (e_1, e_2) in specimens with two section sizes was the same, the width loss ratio (e_2/B) was

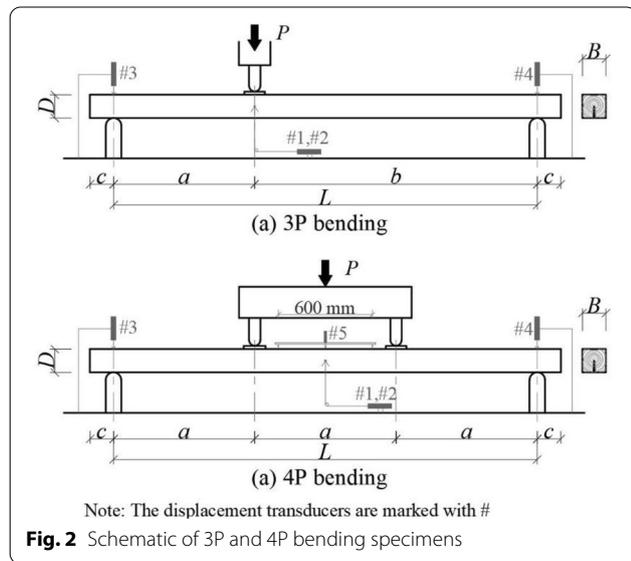


Table 1 Specification of 3P and 4P bending specimens

Specimen	B [mm]	D [mm]	L [mm]	a [mm]	b [mm]	c [mm]	E_f [kN/mm ²]	MC [%]	Number of specimens
H15-3P	150	150	2700	900	1800	150	11.33	14.5	16
H15-4P					–		11.45	14.7	16
H18-3P	180	180	3240	1080	2160	380	11.27	16.5	16
H18-4P					–		11.48	15	16
S15-3P	150	150	2700	900	1800	150	9.27	16.8	16
S15-4P					–		9.39	16	16
S18-3P	180	180	3240	1080	2160	380	8.61	22.4	16
S18-4P					–		8.76	24.3	16

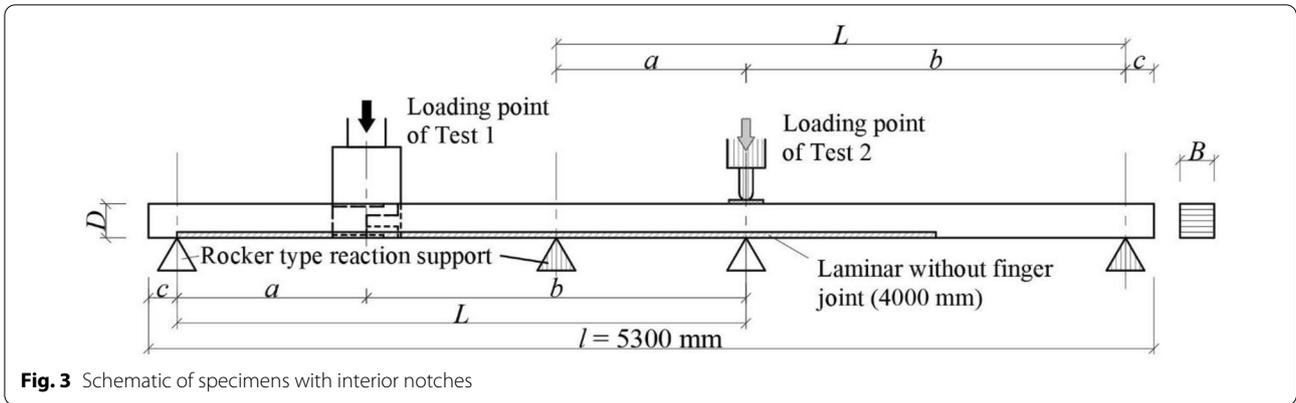


Fig. 3 Schematic of specimens with interior notches

Table 2 Specification of the specimens with interior notches

Specimen	Strength class	B [mm]	D [mm]	L [mm]	a [mm]	b [mm]	c [mm]	ρ [g/cm ³]	Number of specimens
HG15-M2	E95-F315	150	150	3000	1000 (L × 1/3)	2000	150	0.5	10
HG15-M3									
HG15-M4									
HG18-M2									
HG18-M3	180	180	3000	1000 (L × 1/3)	2000	150	0.49	10	
HG18-M4									
SG15-M2									
SG15-M3	E55-F225	150	150	3000	1000 (L × 1/3)	2000	150	0.39	10
SG15-M4									
SG18-M2									
SG18-M3									
SG18-M4	180	180	3000	1000 (L × 1/3)	2000	150	0.41	10	
SG18-M3									
SG18-M4									

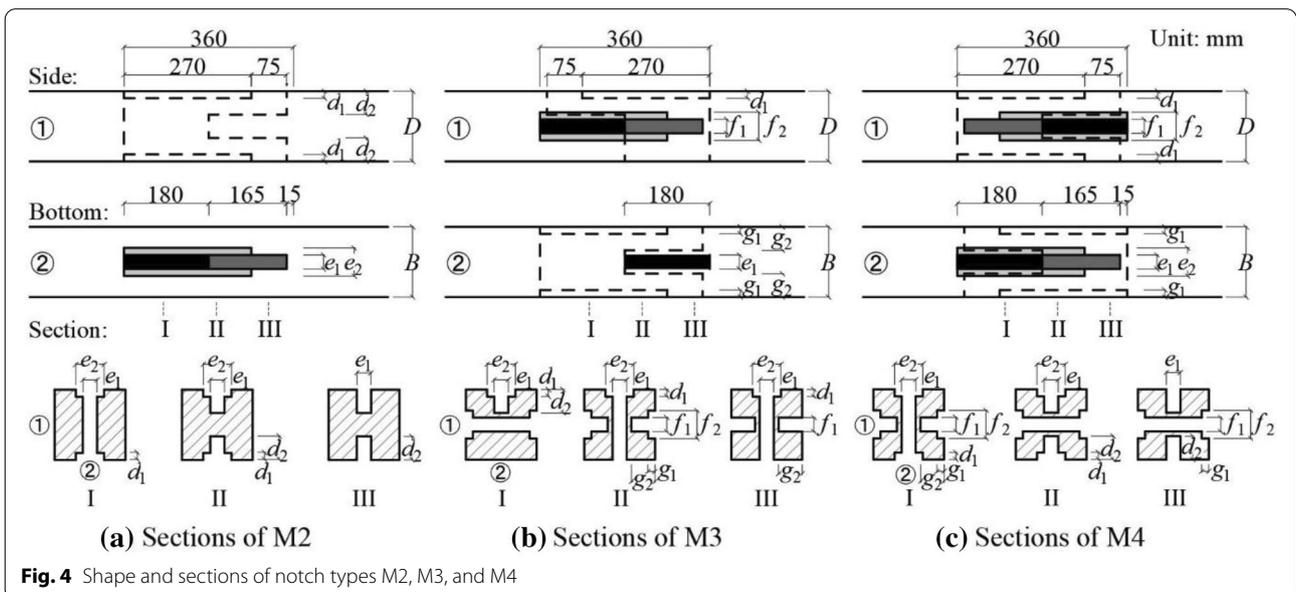


Fig. 4 Shape and sections of notch types M2, M3, and M4

Table 3 Dimensions in the notches of different section sizes (unit: mm)

$B \times D$	d_1	d_2	e_1	e_2	f_1	f_2	g_1	g_2	Width loss ratio (e_2/B)
150 × 150	15	50	30	60	30	60	15	50	0.40
180 × 180	15	60	30	60	30	60	15	60	0.33

relatively larger in specimens with the section size of 150 mm.

Based on the conducted frame tests [1], it was observed that the concentrated load transmitted from the deep beam led to column bending. After confirming the nominal strengths from comparative experiments of 4P and 3P bending, the column strength with interior notches at the point of the deep beam was further identified through the 3P bending test. The location of the deep beam in a frame varies from the middle of the column to close to the main beam, depending on the story height and the opening height as well. Considering the position of deep beams in the conducted frame tests was approximately one-third of the column, a one-third position of the concentrated force was assumed in the 3P bending tests. Hence, the concentrated force was applied at one-third span in Tests 1 and 2 at a crosshead speed of 6 mm/min. Instead of directly applying the load along the centerline of the notch in Test 1, the load was transferred to the

specimen through a block with a tenon made of Douglas fir to simulate the connection between the beam end and the column (Fig. 5). In addition, for the specimens with notch types M3 and M4, a tenon with a cross-section of 30 mm × 180 mm was inserted into the transverse opening to replicate the force transmission at the beam–column joint. Displacement transducers were placed at the load and support points to determine the deflection of the specimens. The names of test specimens included information about the tree species (SG for Japanese cedar Glulam, and HG for Japanese cypress Glulam), section size (15 for a section size of 150 mm, and 18 for a section size of 180 mm), and the notch type (M2, M3, and M4).

Material tests

After the 3P bending tests, tension tests were performed to determine the tensile strength parallel to the bottom laminate grain. Two clear defect-free samples were cut from the undamaged part of the continuous bottom



(a) Test 1: 3P bending with interior notch



(b) Test 2: 3P bending without notches

Fig. 5 Test setup of specimens with and without interior notches

laminate of each specimen and produced according to the JIS standard [17] (Fig. 6). The test speed was adjusted to 0.6–0.8 mm/min to ensure that the maximum force was reached within approximately 300 s.

Results and discussion

Effect of load configuration on flexural properties

Based on the 3P and 4P bending tests on specimens for different tree species and section sizes, the elastic modulus (E_b) and bending strength (F_b) were obtained from the applied load and deflection, using Eqs. (1)–(4). The average values of E_b and F_b of 16 specimens in each group, the corresponding standard deviations (SD), and the 5% lower tolerance limit (TL-5%) of F_b are listed in Table 4:

$$E_{b-3P} = \frac{4P \cdot L^3}{243I \cdot \delta} \left(1 + \frac{27}{20} \left(\frac{E}{G} \right) \left(\frac{D}{L} \right)^2 \right). \quad (1)$$

In Eq. (1), P is the increment in the applied load, δ is the corresponding increment in the deflection (measured

using displacement transducers #1 and #2 in Fig. 2a), L is the span between two lower supports, D is the depth of the specimen, I is the moment of inertia, and $\frac{E}{G}$ is assumed to be 15.

$$E_{b-4P} = \frac{P \cdot a \cdot l^2}{16I \cdot \delta'} \quad (2)$$

In Eq. (2), P is the increment in the applied load, δ' is the corresponding increment in the deflection (measured using displacement transducer #5 in Fig. 2b), a is the distance between the loading point and the support, and l is the length of the displacement section between the load points.

$$F_{b-3P} = \frac{2P_{max} \cdot L}{9Z_0}, \quad (3)$$

$$F_{b-4P} = \frac{P_{max} \cdot a}{2Z_0}. \quad (4)$$

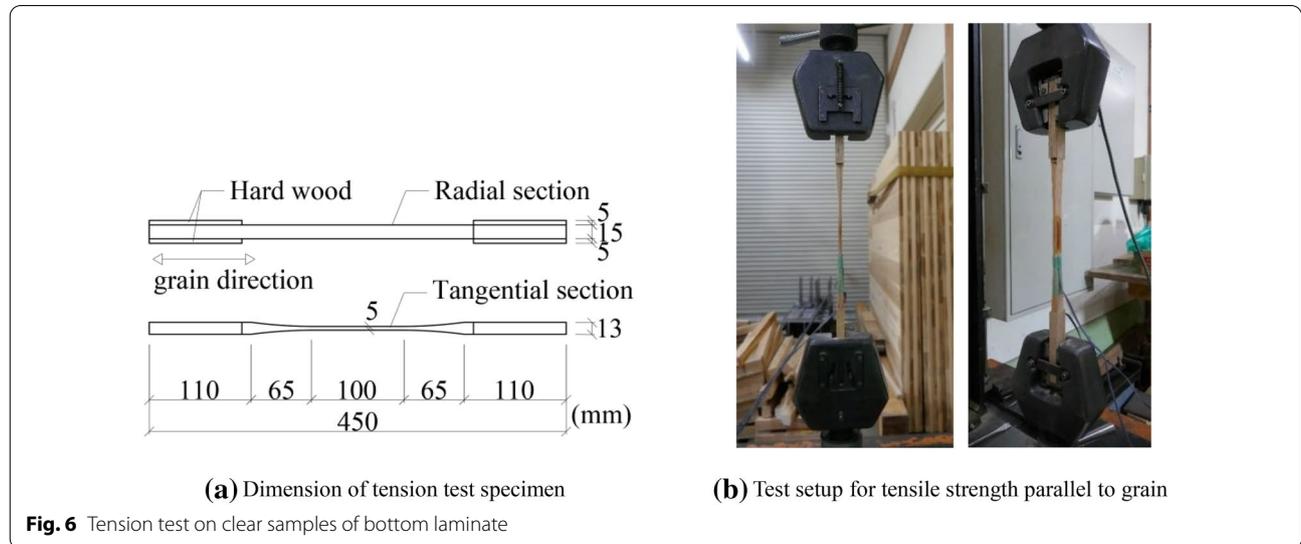


Fig. 6 Tension test on clear samples of bottom laminate

Table 4 Flexural properties of specimens under 3P and 4P bending

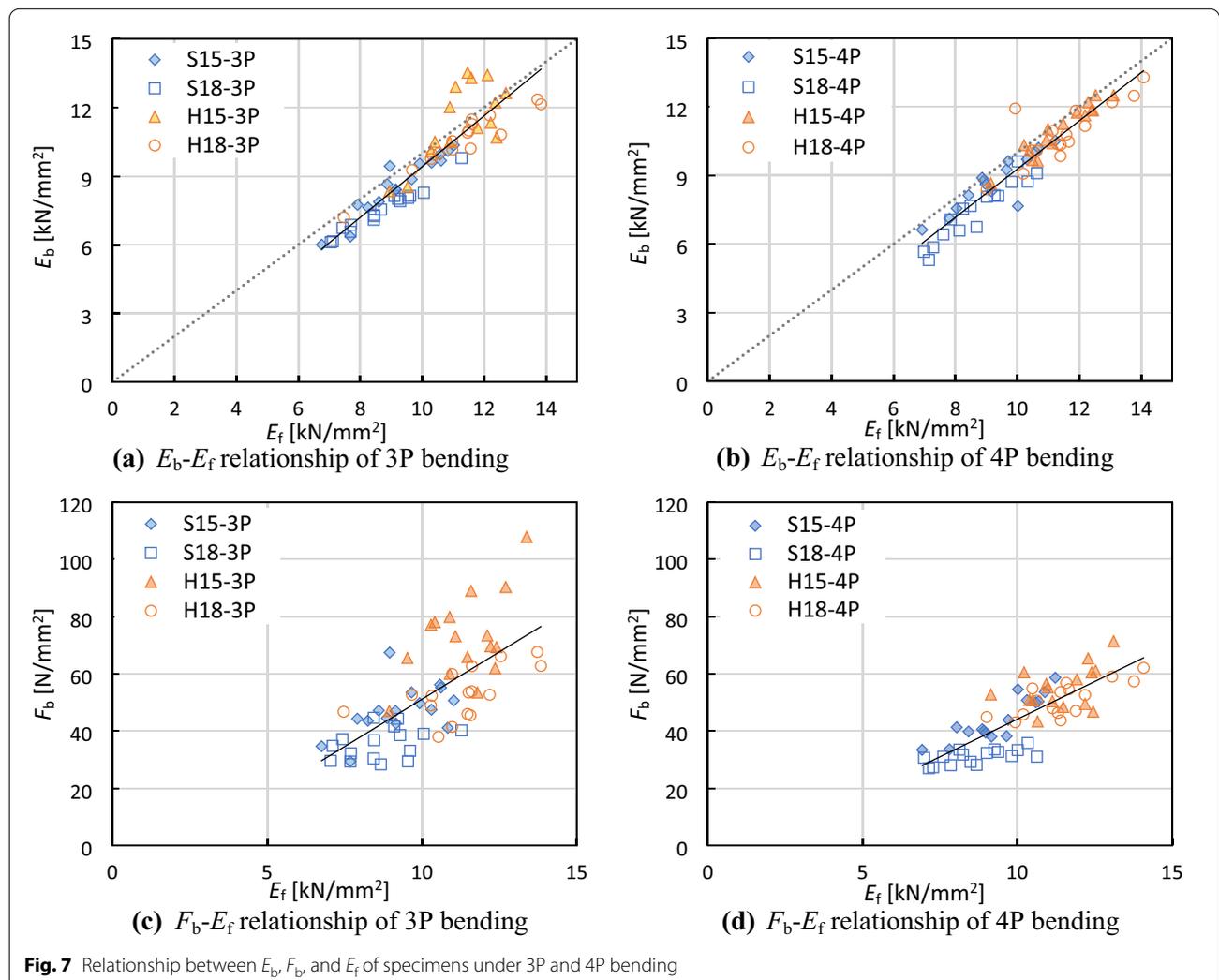
Specimen	E_b [kN/mm ²]	P_{max} [kN]	F_b [N/mm ²]	F_{b-3P} / F_{b-4P} [%]	SD	F_b (TL-5%) [N/mm ²]	TL-5% _{3P} / TL-5% _{4P} [%]
S15-3P	8.66	44.22	47.17	107	8.85	29.72	103
S15-4P	8.74	55.20	44.16		7.75	28.87	
H15-3P	11.63	68.06	72.59	132	14.93	43.15	107
H15-4P	10.99	68.85	55.08		7.41	40.46	
S18-3P	7.49	48.07	35.61	115	5.48	24.24	93
S18-4P	7.46	55.92	31.07		2.53	26.07	
H18-3P	10.54	71.80	53.18	104	8.74	35.95	91
H18-4P	10.83	92.32	51.29		5.92	39.62	

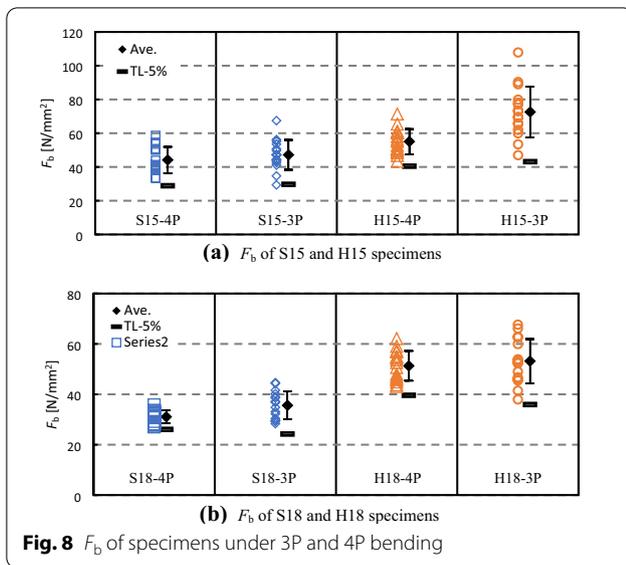
In Eqs. (3) and (4), P_{max} is the maximum force, L is the span between two lower supports, Z_0 is the nominal section modulus, calculated using the width B and depth D of the specimen ($Z_0 = \frac{BD^2}{6}$), and a is the distance between the loading point and the support.

The relationship between the static modulus E_b and dynamic modulus E_f is shown in Fig. 7a, b. A linear relationship between E_b and E_f was confirmed for specimens under 3P and 4P load configurations, while the dynamic value E_f tended to be slightly higher (5%–10%) than E_b that determined from the static bending tests. The relation between E_b and E_f was similar to the range reported by other researchers [18, 19]. In the static bending, the elastic modulus was calculated from the deformation at the loading point, the influence of the defects around the loading point and viscous deflection were considered as possible contributors to the lower value of E_b . The relationship between the bending strengths F_b and E_f

is depicted in Fig. 7c, d, and a generally linear relationship between F_b and E_f was observed. A higher coefficient of determination was obtained through 4P bending ($R^2=0.66$) than 3P bending ($R^2=0.47$).

In terms of the mean value of F_b , the 3P bending strength was higher than the 4P bending strength with an average increase rate of 1.14 for both the Japanese cedar and cypress specimens of 150-mm and 180-mm section sizes. However, because the load-bearing capacity of specimens under 3P bending was significantly influenced by the quality of timber near the concentrated load, the standard deviation of the 3P bending strength was also higher than that of 4P bending strength (Fig. 8). Therefore, a comparison of the 5% lower tolerance limit of bending strength showed that the difference between 3 and 4P bending was much decreased. Compared with other groups, the strength difference of H15-3P and H15-4P specimens was larger. In addition to the





influence of load configurations, one factor was that the material properties of H15-3P specimens were relatively better, which was also reflected in higher values of elastic modulus.

Effect of interior notch on flexural properties

Observed damage of columns with different notch types

In both the 3P bending test with and without interior notches, rupturing occurred on the tensile side of the specimen around the loading center and extended toward the upper laminates (Fig. 9). The irregularity of the traditional mortise shape was considered, and the failure

position and the corresponding section shape (Fig. 4) of each group of 10 specimens were sorted out, as listed in Table 5. Most ruptures occurred around the sharp corners of the bottom notches, particularly for the specimens with additional shallow but wider notches on the tensile side (M2 and M4), and the failure position indicated higher correlations with the broader notch boundary, which corresponded to section shapes I and II.

The transversal opening effect on the failure mode was mainly attributed to the decrease in the net section because no significant shear failure of the specimens with notch types M3 and M4 occurred. Therefore, the failures of the specimens with notch M3 and M4 were more concentrated at the weakest net section (Shape II) than that of the specimens with notch M2. For the specimens with a section size of 180 mm, the distribution of failure positions on different section shapes tended to be more even, due to the relatively less significant section loss of the notches.

Bending properties of columns with and without interior notches

The flexural properties of the specimens with an interior notch (Test 1) and without notches (Test 2), including the mean values of elastic modulus (E_b), maximum force (P_{max}), plastic ratio (δ_{max}/δ_y), bending strength (F_b), the corresponding standard deviation (SD) of F_b , and 5% lower tolerance limit (TL-5%) of F_b were determined (Table 6). The bending strengths of specimens with different notch types could also be computed using Eq. (3), and the nominal section modulus (Z_0) was calculated based on the net section corresponding



Table 5 Distribution of failure position in different section shapes

Section	SG15			HG15			SG18			HG18		
	M2	M3	M4									
I	40%	10%	10%	60%	20%	30%	30%	10%	60%	70%	30%	40%
II	50%	80%	60%	30%	70%	70%	40%	70%	40%	30%	40%	50%
III	10%	10%	30%	10%	10%	0%	30%	20%	0%	0%	30%	10%

Table 6 Flexural properties of specimens with and without interior notches

Specimen		E_b [kN/mm ²]	P_y [kN]	P_{max} [kN]	δ_{max} / δ_y	F_b [N/mm ²]	SD	F_b (TL-5%) [N/mm ²]
SG15-M2	Test 1	22.26	6.75	1.27	25.03	41.54 (42.23) *	8.74 (8.32)	23.14 (24.72)
	Test 2	32.40	7.38	1.12	35.03	41.52	4.35	32.37
SG15-M3	Test 1	22.92	6.95	1.10	24.44	38.97 (39.51)	6.20 (7.27)	25.91 (24.22)
	Test 2	28.43	7.10	1.11	31.06	36.82	6.01	24.17
SG15-M4	Test 1	23.40	6.62	1.17	25.98	42.45 (44.90)	4.70 (6.56)	32.57 (31.09)
	Test 2	28.61	7.23	1.47	36.40	43.14	1.98	38.98
HG15-M2	Test 1	37.58	10.66	1.42	44.46	74.00 (75.02)	13.33 (12.12)	45.95 (49.53)
	Test 2	43.23	12.12	1.93	63.94	75.78	5.47	64.28
HG15-M3	Test 1	36.12	11.46	1.66	45.64	72.32 (73.79)	10.96 (10.36)	49.27 (51.99)
	Test 2	45.40	12.29	1.45	56.81	67.33	12.32	41.41
HG15-M4	Test 1	33.00	10.43	1.50	40.30	69.28 (69.63)	10.51 (10.67)	47.16 (47.18)
	Test 2	44.91	11.91	1.56	58.64	69.5	10.49	47.43
SG18-M2	Test 1	52.82	8.57	1.57	68.24	59.46 (61.33)	6.94 (6.56)	44.86 (47.54)
	Test 2	58.45	9.42	1.78	77.18	52.93	5.74	40.87
SG18-M3	Test 1	54.42	8.95	1.27	64.07	55.11 (55.69)	4.58 (4.75)	45.48 (45.70)
	Test 2	62.19	9.49	1.58	77.88	53.42	5.42	42.02
SG18-M4	Test 1	51.71	8.68	1.38	61.65	55.90 (56.04)	5.48 (5.44)	44.37 (44.59)
	Test 2	63.81	9.37	1.46	75.47	51.76	4.91	41.42
HG18-M2	Test 1	64.97	10.48	1.26	73.91	66.27 (66.42)	9.08 (9.08)	47.17 (47.31)
	Test 2	77.56	11.40	1.33	94.31	64.68	9.14	45.44
HG18-M3	Test 1	69.68	11.32	1.43	83.78	70.74 (72.83)	6.52 (7.08)	57.02 (57.94)
	Test 2	85.54	11.88	1.31	100.59	68.99	11.05	45.73
HG18-M4	Test 1	67.95	11.32	1.32	78.54	70.39 (71.39)	9.56 (10.18)	50.28 (49.97)
	Test 2	86.82	12.06	1.23	98.44	67.52	10.84	44.72

* Data in brackets were obtained from the same Z_0 based on the weakest net section of each notch type (Fig. 10)

to the failure position of each specimen. The ratio of Z_0 between the entire section and the net section of each notch type is listed in Table 7. Considering the convenience in practical design, the brackets in Table 6 also

listed the bending strength obtained from the same Z_0 based on the weakest net section of each notch type (Fig. 10). The difference between bending strengths

Table 7 Ratio of Z_0 between entire section and net section of different notch types

Section shape	Z_{0-M2} / Z_0		Z_{0-M3} / Z_0		Z_{0-M4} / Z_0	
	150 × 150 mm	180 × 180 mm	150 × 150 mm	180 × 180 mm	150 × 150 mm	180 × 180 mm
I	0.70	0.76	0.82	0.86	0.69	0.75
II	0.71	0.77	0.73	0.79	0.69	0.76
III	0.81	0.84	0.74	0.79	0.79	0.83

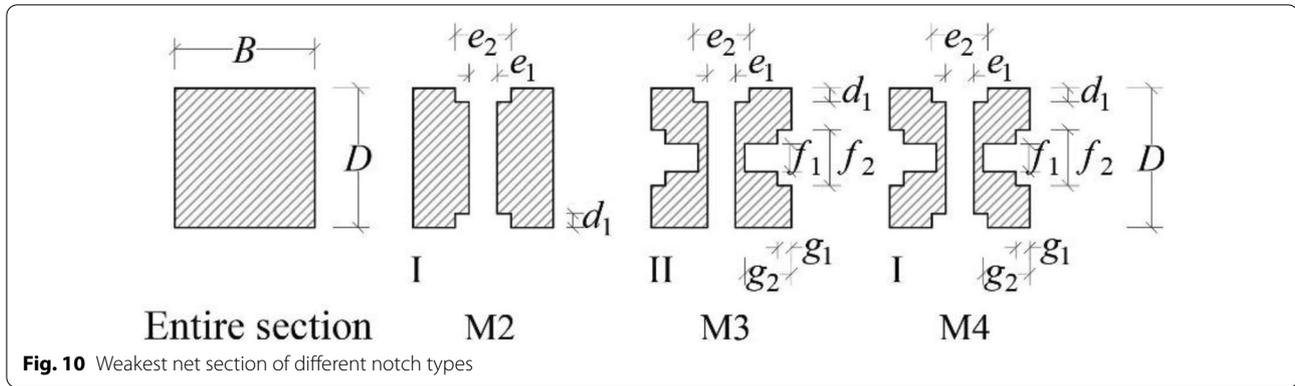


Fig. 10 Weakest net section of different notch types

calculated from the weakest net section and that from the net section of failure positions was insignificant.

It was found that the bending strength of specimens with a notch on average obtained using the nominal section modulus of the net section was generally consistent with those of specimens without notches. Overall, the standard deviation of the bending strength of specimens produced with Japanese cypress was higher than that of Japanese cedar. From the standard deviation of bending strength, the overall tendency was not clear. However, compared with the specimens with the notch type M3, the value of SD in Test 1 with a notch was higher than that in Test 2 without notches for specimens with notch types M2 and M4. The possible influence was reflected in a larger section loss on the tensile side caused by the notch shape. In addition, this difference between SD in Test 1 and Test 2 in specimens of the 150 mm section size was more obvious than that of 180 mm for the same notch type, which was influenced by a higher percentage of width loss ratio on the tensile side of the specimens. Based on the comparison between specimens with notch types M2 and M4, the effect of the transverse opening and notch on the bending strength was insignificant. When the transverse opening was filled with a tenon, the transmission of the applied load from the compressive side to the tensile side was facilitated, reducing the stress concentration at the opening.

Because the bending performance of the Glulam specimens was significantly influenced by the tensile strength of the outer laminate on tensile side, the tensile properties of the outer laminate were obtained through the material tests (Table 8). Both the elasticity in tension ($E_{t,0}$) and tensile strength (σ_t) of the SG 18 specimens were higher than those of the SG 15 specimens, and consistent with the strength difference obtained through bending tests. It could be confirmed that the difference of bending strength between SG 15 and SG 18 specimens was mainly caused by the tensile properties of the outer

Table 8 Tensile properties of outer laminate on tensile side

Specimen	P_{max} [kN]	$E_{t,0}$ [kN/mm ²]	σ_t [N/mm ²]	SD	σ_t (TL5%) [N/mm ²]
SG 15	4.38	7.85	58.02	7.39	43.74
SG 18	5.25	9.48	69.96	8.53	53.47
HG 15	9.11	11.61	121.68	20.27	82.53
HG 18	9.68	11.98	125.50	16.03	94.54

laminate. The tensile property of the HG 15 and HG 18 specimens was similar, also be consistent with the difference in bending strength.

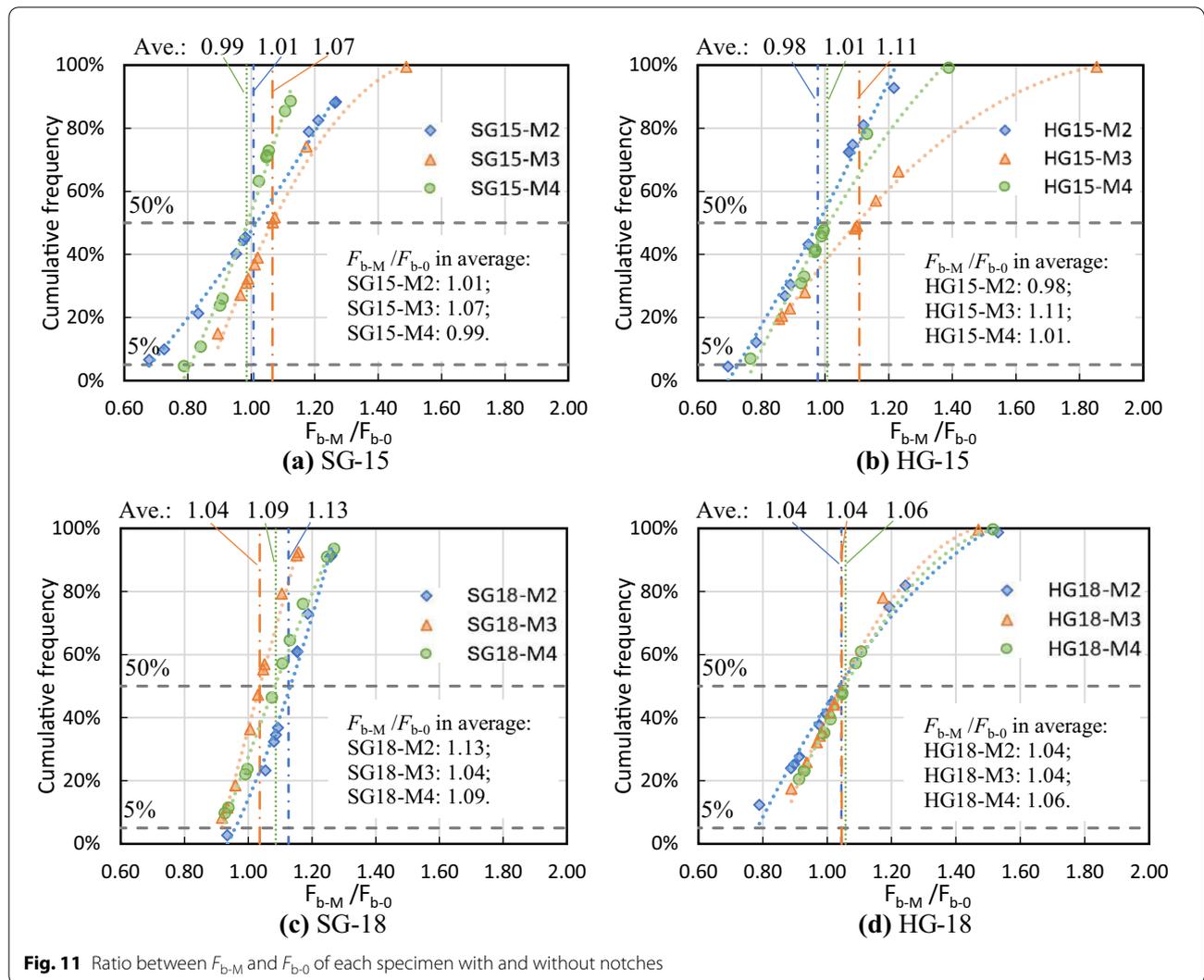
Reduction of bending strength of columns with interior notches

To distinguish the influence of interior notches, the bending strength F_b obtained from the condition with a notch (Test 1) was marked as F_{b-M} , and F_b obtained from the condition without notches (Test 2) was marked as F_{b-0} . Figure 11 shows the cumulative distributions of the ratio of the bending strength with and without notches for each specimen. Coefficient β is defined as the ratio between bending strength of columns with and without interior notches, as expressed in Eq. (5):

$$\beta = \frac{f_{b-M}}{f_{b-0}} \tag{5}$$

In Eq. (5), f_{b-0} is the referenced bending strength obtained from the mean value of each of the 30 specimens of Test 2 without notches; f_{b-M} is the mean value of bending strength of each of the 10 specimens with different interior notches, determined through Test 1.

β can also be regarded as the ratio of the effective section modulus (Z_e) to the nominal section modulus (Z_0), which reflects the effects of stress concentration at the sharp interior corner of the notch on the reduction of allowable bending strength. However, the obtained values



of β were approximately 1.0 in both Japanese cypress and cedar specimens with three different notch types (Table 9), which were significantly higher than the regulations in AIJ standard for the reduction factor of a tension-side notched beam ($\beta = 0.45 - 0.6$) [2] due to stress concentration. It is noteworthy that for a notch that normally penetrates through the beam in the width direction [2, 11–13], the strength reduction caused by both the section reduction and stress concentration is highly correlated to the notch depth. When considering the notch

types for the traditional tenon–mortise joints on the columns, the notch width is only approximately 1/3 of the column width. Based on the experimental statistics of the column specimens with two section sizes and three different notch types, it can be inferred that the continuous timber on both sides of the notch has a beneficial effect on maintaining a higher strength of the tensile side under bending and reducing the stress intensity at the notch corner. Even when the notch depth to column depth ratio reaches 1/3, and the width loss ratio on tensile side of the

Table 9 Values of coefficient β of specimens with different notch types

SG15			HG15			SG18			HG18		
M2	M3	M4									
1.03	0.96	1.05	1.04	1.02	0.98	1.13	1.05	1.06	0.99	1.05	1.05

column reaches 0.4 (SG15 and HG 15 specimens), there is no additional reduction in the bending strength, but the standard deviation of the test data tends to increase. Hence, in addition to the notch depth, the width loss ratio on the tensile side should also be regarded as a non-negligible factor in evaluating the reduction of flexural properties of columns with interior notches in traditional timber frames.

Conclusions

Columns with interior notches in traditional Japanese timber frames were selected as research object in this study. The difference in the bending strengths of columns under 3P and 4P load configurations was investigated, and the load-bearing capacities of columns with different types of interior notches were evaluated through experimental tests and statistical analyses. The following conclusions were drawn:

- (1) The mean bending strengths obtained through 3P bending tests on the columns made of Japanese cedar and Japanese cypress were higher than those obtained through 4P bending tests, with an average increase rate of 1.14 for different section sizes. However, the difference in TL5% of the bending strength between these two load configurations decreased significantly owing to the higher standard deviation of the experimental data under 3P bending.
- (2) Although the mean values of bending strengths of the specimens with three different types of notches were consistent with those without notches, the standard deviations of the load-bearing capacity were higher in specimens with a higher percentage of width loss ratio on the tensile side. Combined with the failure phenomenon, the fracture position showed higher correlations with the boundary of the shallow but wider notch on the tensile side. The effects of the transverse opening and notch on the bending strength were insignificant.
- (3) The obtained coefficient β reflecting the effects of stress concentration at the notch was approximately 1.0 in both Japanese cypress and cedar specimens with three different notch types. It can be inferred that the continuous timber on both sides of the notch has a beneficial effect on maintaining a higher strength and reducing the stress intensity around the notch.

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Authors' contributions

ZL performed the bending tests and analysis of columns with interior notches and was a major contributor in writing the manuscript. HI supervised the project and planned the experiments. AK performed the comparative bending tests of 3P and 4P load configurations. TN contributed to the improvement of statistical analysis. YA and NK aided in the verification of the result and worked on the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and analyzed in the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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