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ORIGINAL ARTICLE

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Fracture of multiply-bolted joints under lateral force perpendicular to wood grain

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Abstract The crack initiation and propagation of multiply-bolted joints subjected to lateral forces perpendicular to the grain were analyzed. Two types of bolted joint were subjected to lateral loads perpendicular to the grain. One had joints of two bolts aligned with the wood grain (type H), and the other had joints of two or three bolts aligned perpendicular to the grain (type V). The crack initiation and propagation were analyzed by means of the average stress method (ASM) and linear elastic fracture mechanics (LEFM), respectively. The maximum loads calculated by LEFM agreed comparatively well with the experimental results, and it was proved that the LEFM was an appropriate tool to analyze the fracture of multiply-bolted joints subjected to a force perpendicular to the grain. It was also found that the multiply-bolted joints failed with the fracture of the wood before the joints yielded, and that it caused a considerable decrease of the maximum loads. The reduction of strength should be considered in the design of multiply-bolted joints subjected to lateral forces perpendicular to the grain.

Key words Bolted timber joints · Fracture mechanics · Average stress method · Yield load

Introduction

Fractures in wood comprise a major cause of brittle failure in timber structures. They produce serious damage to timber structures subjected to seismic action by reducing energy dissipation. Fracture occurs frequently at joints subjected to a force perpendicular to the wood grain. This failure is not always predictable because the design of timber joints is generally based on the yield theory,[1–3] which does not include failure of joints due to fracture of the wood. Fracture mechanics is one of the methods by which to analyze the fracture of timber structures.[4–6]

In a previous paper[4] the fracture of single-bolted joints subjected to a lateral force perpendicular to the grain was analyzed by means of the average stress method (ASM) and linear elastic fracture mechanics (LEFM). It showed that the ASM and LEFM were appropriate tools for predicting crack initiation and propagation in bolted timber joints, respectively. In that study the timber joints of two bolts aligned with the grain and those of two or three bolts aligned perpendicular to the grain were subjected to lateral loads perpendicular to the grain. The experimental results were compared with the analyses done by the ASM and LEFM.

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Theory

Crack initiation

The crack-initiating load is calculated by the ASM using the finite element model. The criterion for crack initiation is expressed as follows;

$$\frac{1}{l_c}\int_0^{l_c} \sigma_{yy}(P)dx \geq f_t \qquad (1)$$

where l_c is the characteristic distance, P is the lateral load, and f_t is the tensile strength of wood perpendicular to the grain. The definitions of directions x and y are given in Fig. 3. The value of l_c was determined by the crack-initiating load (P_c) obtained from the lateral loading tests of bolted joints and the stress distribution σ_{yy} along the x-axis in the finite element models of those joints. It was set at 2.84 mm based on experiments conducted at the LMT[7] for 4.76 MPa of the tensile strength perpendicular to the grain (f_t). The value σ_{xy} was neglected in Eq. (1) because it was far smaller than σ_{yy}.

Crack propagation

The crack-propagating load is calculated by the stress intensity factor in mode I (K_I), defined as follows:

$$K_I = \lim_{r \to 0} \sigma_{yy}(r)\sqrt{2\pi r} \tag{2}$$

where $\sigma_{yy}(r)$ is the tensile stress perpendicular to the grain at distance r from the crack tip. The criterion for crack propagation is

$$K(P, A) \geq K_{Ic} \tag{3}$$

where A is the crack length and K_{Ic} is the critical stress intensity factor in mode I. The value of K_{Ic} was set at $0.439\,\text{MPa}\sqrt{\text{m}}$ from the previous study.[4] The criterion for the unstable crack propagation is

$$\frac{\partial K(P, A)}{\partial A} \geq 0 \tag{4}$$

Materials and methods

Specimens

The specimens are shown in Fig. 1. Specimens consisted of spruce (*Picea* sp.), glued laminated wood, and 12mm thick steel side plates on both sides of the wooden member, connected with bolts 16mm in diameter (d). The glued laminated wood was made of laminae 30mm thick with an average density of $440\,\text{kg/m}^3$. The quality of steel used for the side plates and bolts was Japanese Industrial Standard (JIS) SS 400. The predrilled holes of wooden members were equal to or slightly larger than the bolt diameters, and the diameters of the bolt holes of steel plates were 1mm larger than the bolt diameter. The thickness of the wooden member was 64mm ($4d$), and the length varied from 800 to 960mm depending on the bolt spacing. The edge distance of the extreme fastener was 64mm ($4d$).

The specimens were divided into two groups, as shown in Fig. 1. Type H specimens had joints of two fasteners aligned with the grain and spaced at 64mm ($4d$), 112mm ($7d$), and 160mm ($10d$). Type V specimens had joints of two or three fasteners aligned perpendicular to the grain and spaced at 64mm ($4d$).

Test method

Three specimens of each type were subjected to lateral loads, as shown in Fig. 1. The quasistatic tensile loads were applied to the steel side plates by a hydraulic jack, and the relative displacement between the steel plate and wooden member was measured by four electric displacement transducers. The nuts were attached to the joints with little tightening. The lateral loads increased at a constant rate until one of the joints failed.

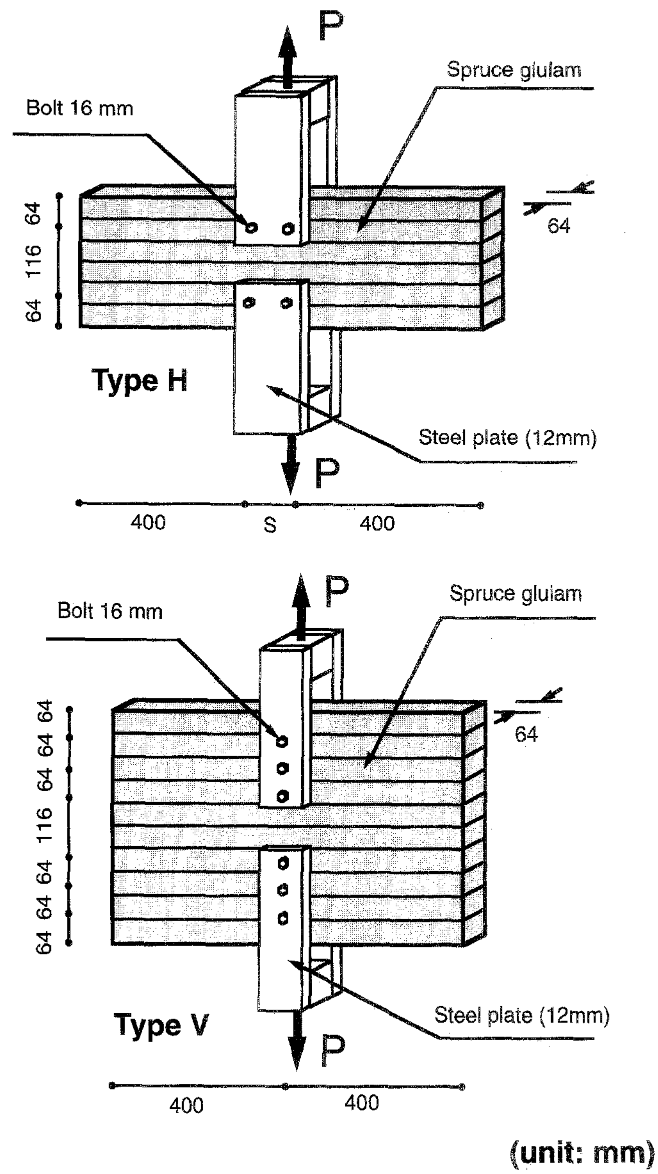

Fig. 1. Specimens and lateral loading test

Modeling: finite element model

Tested joints were modeled with the finite elements, as shown in Fig. 2. One-quarter of the specimen was modeled considering the symmetry. The assumption for the modeling was the same as in the previous study of a single fastener[4]: The contact between the wood and the bolt was complete, and there was no friction on them; the plane stress conditions were applied, and there was no noticeable deformation of the bolt. Young's modulus of spruce was assumed to be 15000MPa in the longitudinal direction and

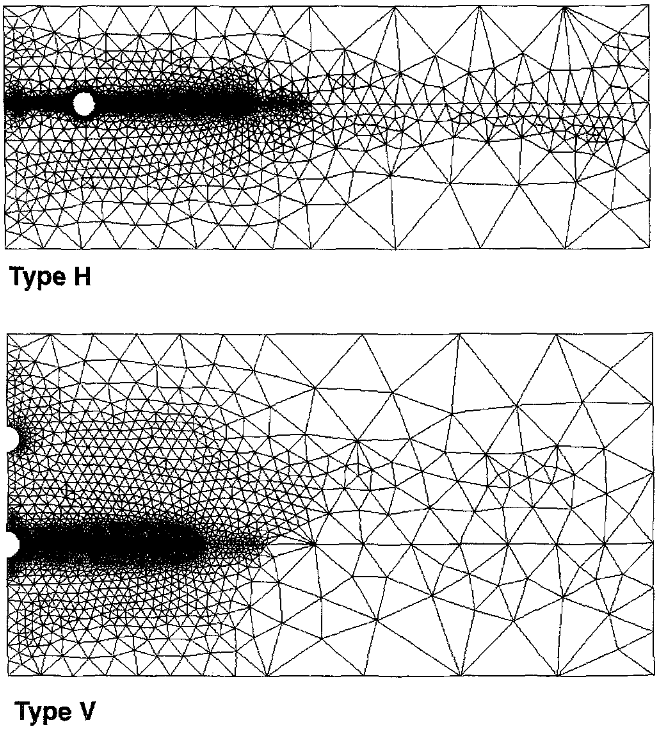

Fig. 2. Finite element mesh of the type H specimen of bolt spacing 7*d* and the type V specimen of two bolts

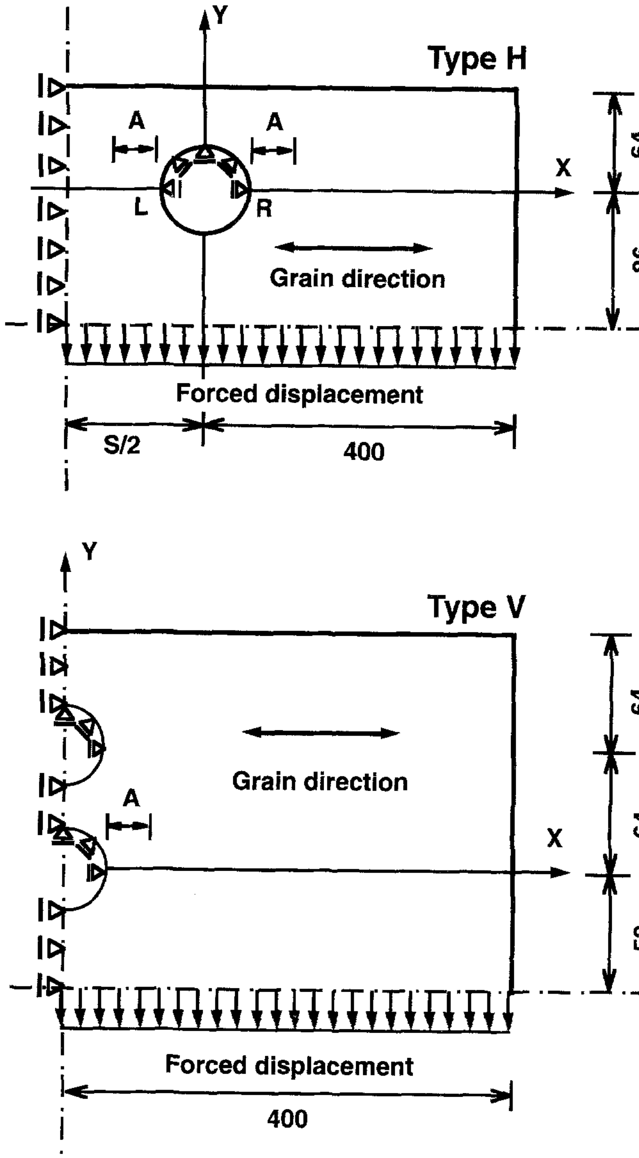

Fig. 3. Boundary conditions in finite element models

600MPa in the transverse direction; 700MPa and 0.5 of the shear modulus and Poisson's ratio, respectively, were assumed.

Figure 3 shows the boundary conditions of the model. The upper half of the holes were fixed in the radial direction and were free in the tangential direction. The forced displacements were applied downward at the lower boundaries. The FEM code CASTEM 2000, developed by the French Atomic Energy Commissariat (CEA), was used for the analysis.

Results and discussion

Crack initiation

Figure 4 shows the tensile stress perpendicular to the grain (σ_{yy}) near the bolt holes along the x-axis when the average stress perpendicular to the grain reached 4.76MPa in the type H specimens. This finding shows that stress in the right side of the hole was slightly higher than that in the left side, and that the crack started at the right boundary of the hole. The stress perpendicular to the grain at the right boundary of the hole showed almost constant values around 6.3–6.4MPa regardless of the bolt spacing. The stress at the left boundary varied from 5.74 to 5.92 to 6.14MPa, respectively, for the bolt spacing of 4*d*, 7*d*, and 10*d*. This finding indicates that the tensile stress perpendicular to the grain was more concentrated at the right boundary (outer side) than the left boundary (inner side) when the bolt spacing was 4*d*, but there was little difference at the right and left boundaries when the bolt spacing was 10*d*.

Figure 5 shows the tensile stress perpendicular to the grain (σ_{yy}) near the bolt holes along the x-axis when the average stress perpendicular to the grain reached 4.76MPa in the type V specimens. Thus the stress distribution along the x-axis of the lowest bolt of the specimen with two or three fasteners was similar to that of the specimen with a single fastener. The stress perpendicular to the grain at the bolt hole boundary of the lowest bolt was approximately 6.15MPa regardless of the number of bolts. The stress of the second and third upper bolts was approximately 40% and 60% smaller, respectively, than that of the lowest bolt. These results indicate that the stress perpendicular to the grain was concentrated mostly at the lowest bolt, and the upper bolts contributed less than the lowest bolt against

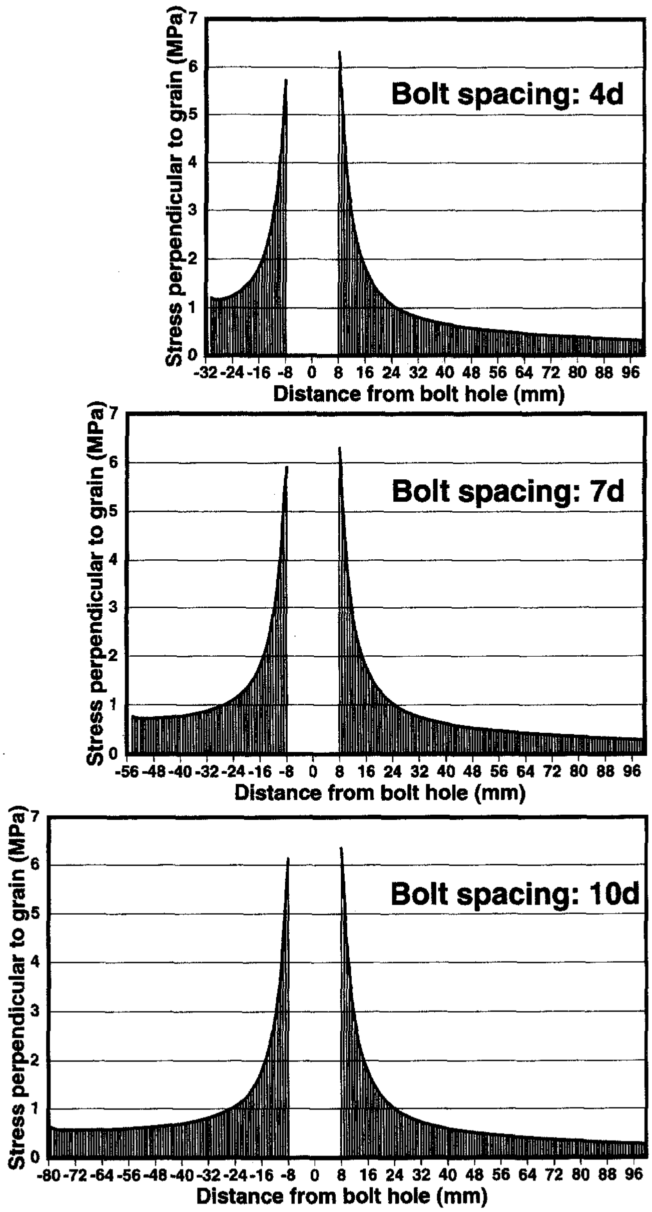

Fig. 4. Stress perpendicular to the grain near the bolt hole along the x-axis in type H specimens

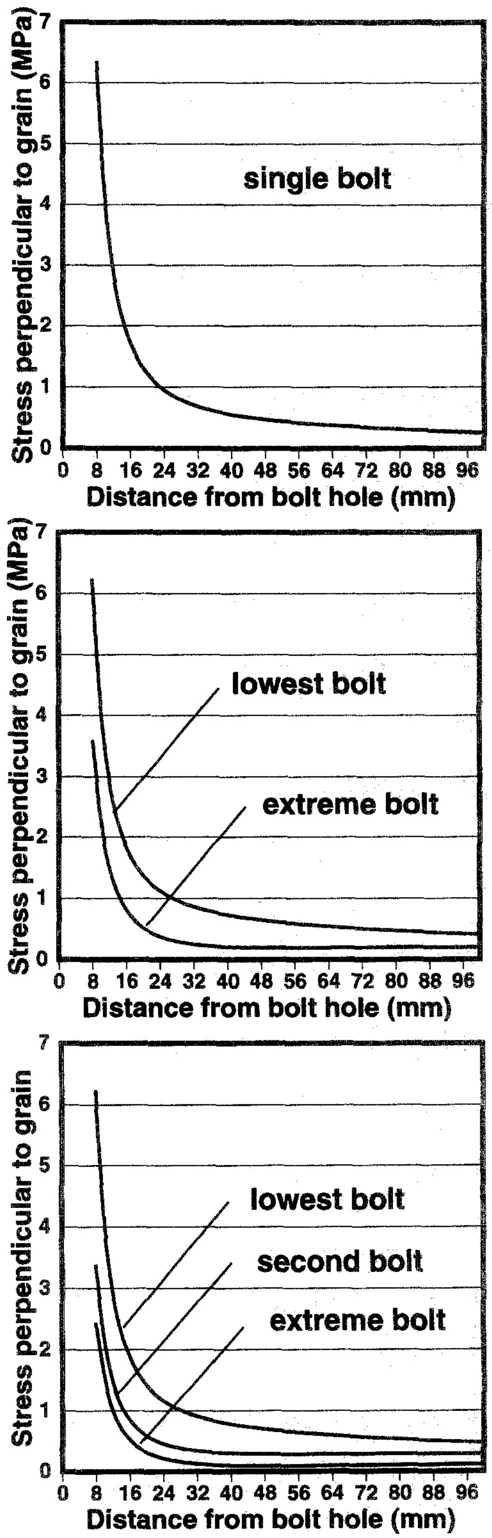

Fig. 5. Stress perpendicular to the grain near the bolt holes along the x-axis in the type V specimens

the crack initiation when the multiple bolts were aligned perpendicular to the grain.

The point of stress at the crack-initiation varied within the range 6.1–6.4MPa for all types of joint tested in this study. This result ensures that the location and the approximate force on the initiating crack can be predicted with the point of stress if the finite meshes are sufficiently fine and there is no problem of singularity. The ASM was applied in this study to obtain accurate results.

Crack propagation

Figure 6 shows the process of the crack propagation in the type H specimens when the bolt spacing was 7*d*. Note that the crack first propagated almost symmetrically in both directions until it propagated up to 1.2*d*. At that point crack propagation on the right side had almost stopped, and the left crack continued propagating. Finally, two cracks that had propagated from both holes met at the center of the specimen. The lateral load per bolt showed an almost con-

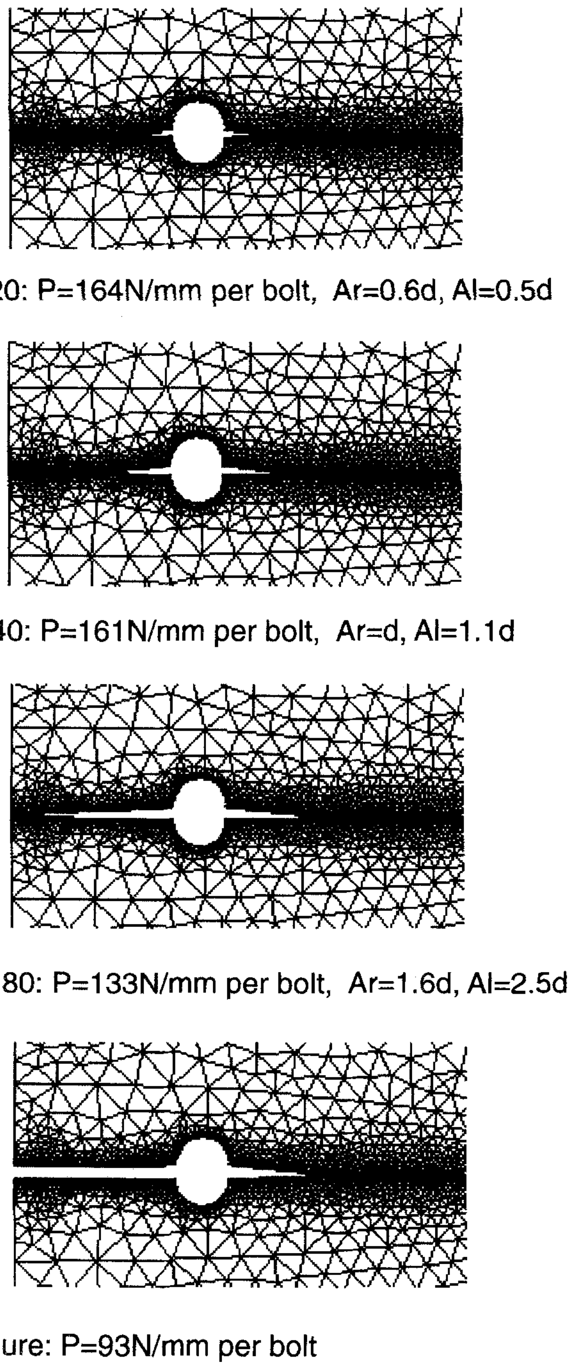

Fig. 6. Simulation of the crack propagation process in the type H specimens of the bolt spacing 7*d*

stant value of 160 N/mm until the crack propagated to 1.5*d*, and it then decreased gradually as the crack propagated. The lateral load decreased suddenly to 93 N/mm when the crack reached the center of the specimen.

Figure 7 shows the relation between the load and the crack length in type V specimens. It shows that the load increased gradually as the crack propagated up to 2.0–2.5*d* and then decreased gradually as the crack propagated. Hence, crack propagation was stable at the beginning but became unstable when it reached 2.0–2.5*d* in the type V specimens.

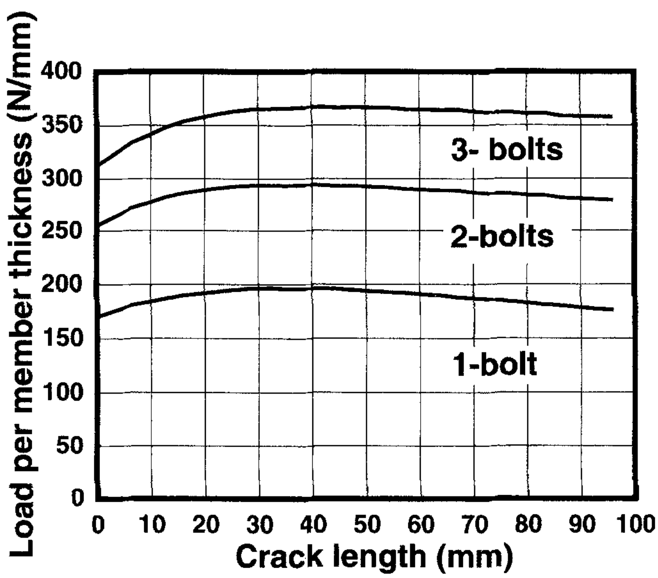

Fig. 7. Relation between crack length and lateral loads per member thickness

Load-carrying capacity

The maximum loads calculated by LEFM, the crack-initiating loads calculated by the ASC, and the yield loads in the type H and V specimens are compared with the experimental results in Table 1. All the results in Table 1 are expressed as the value per member thickness and per bolt.

The maximum loads calculated by LEFM were 4%–20% higher than the experimental results in the type H specimens; both crack-initiating loads and maximum loads increased slightly as the spacing between the bolts increased. The maximum loads calculated by LEFM showed comparatively good agreement with the experimental results in the type V specimens; and both crack-initiating loads and maximum loads per bolt decreased markedly as the number of bolts increased.

The maximum loads obtained from the experiments were compared with the yield strength calculated by the yield theory.[2,8] The calculated yield strength of the joint that had a single bolt 16 mm in diameter with steel side plating was 205 N/mm when the embedding strength of the wood and the yield moment of bolt were, respectively, 12.8 MPa and 218 Nm.[4] The calculated yield strength of the joint with a single bolt was almost the same or slightly higher as the experimental maximum load. However, the maximum loads of the type H and V specimens were, respectively, 25%–35% and 35%–41% smaller than the calculated yield strength, indicating that all the tested joints of multiple fasteners failed with fracture of the wood before the joints yielded. It is important to predict the fracture before the yielding of the fasteners when multiple joints are subjected to a force perpendicular to the grain.

In the type H specimens the crack-initiating loads calculated by the ASM and the maximum loads calculated by LEFM were, respectively, 4%–15% and 9%–18% smaller than those of the joints with a single bolt. In the type V

Table 1. Comparison of the calculated maximum loads and crack-initiating loads with the experimental results

Specimen type	No. of bolts	Bolt spacing	Experiment: Maximum loads[a] (N/mm)	Experiment: Ratio to yield load	LEFM: Maximum loads (N/mm)	LEFM: Ratio to single bolt	ASC: Crack initiation (N/mm)	ASC: Ratio to single bolt
Single bolt	1	NA	193	0.941	195 (1.01)	1.0	170 (0.881)	1.0
Type V	2	4*d*	134	0.654	146 (1.09)	0.749	128 (0.955)	0.753
	3	4*d*	120	0.585	121 (1.01)	0.621	104 (0.867)	0.612
Type H	2	4*d*	133	0.649	159 (1.20)	0.815	144 (1.08)	0.847
	2	7*d*	163	0.795	169 (1.04)	0.867	155 (0.951)	0.912
	2	10*d*	154	0.751	177 (1.15)	0.908	163 (1.06)	0.959

Numbers in parentheses represent the ratio to the maximum loads in experiments
LEFM, linear elastic fracture mechanics; ASM, average stress method; NA, not available; N/mm, load per member thickness; *d*, bolt diameter (16 mm)
[a] Average of three specimens per member thickness and per bolt

specimens the crack-initiating loads and the maximum loads were 25%–38% smaller than those of the single-bolted joints. These results indicate that the maximum loads were considerably decreased when the multiply-bolted joints were subjected to a force perpendicular to the grain. The reduced strength should be considered when designing this type of joint.

Conclusions

It was proved that the multiply-bolted joints failed with a fracture of the wood before yielding of the joints when they were subjected to a force perpendicular to the grain. Thus it is important to predict fracture of the wood when designing multiply-bolted joints. The load-carrying capacity of multiply-bolted joints was predicted by means of LEFM, and it was proved that LEFM was an appropriate tool for analyzing fractures of multiply-bolted joints. Because only bolted joints subjected to mode I failure were analyzed in this study, additional studies should be done on joints subjected to the coupling of modes I and II to develop design methods for predicting fractures of bolted timber joints.

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