J Wood Sci (2003) 49:383–391
DOI 10.1007/s10086-002-0497-3

ORIGINAL ARTICLE

Kei Sawata · Motoi Yasumura

Estimation of yield and ultimate strengths of bolted timber joints by nonlinear analysis and yield theory

Received: May 23, 2002 / Accepted: October 18, 2002

Abstract A finite element nonlinear analysis was conducted on bolted timber joints under lateral loads parallel and perpendicular to the grain. The results obtained from this analysis were compared with the experimental results and calculated values based on the yield theory. The analysis and experiment were performed on double shear bolted joints parallel and perpendicular to the grain with steel side plates and a slotted-in steel plate. It was found from the analysis that the yielding of wood and bolt occurred before the overall yielding of the bolted joint. Shear strength of bolted joints calculated from the yield theory using the embedding yield strength of wood and the yield moment of the bolt showed comparatively good agreement with the shear strength evaluated by 5% offset of the load–slip curve in the experiment and analysis. The shear strength of the bolted joint calculated from the yield theory using the embedding ultimate strength of wood and the ultimate moment of the bolt agreed quite well with the shear strength evaluated by the maximum load up to 15mm slip in the analysis. The former, parallel and perpendicular to the grain, were 11% and 34%, on average smaller than the latter in the experiment.

Key words Nonlinear analysis · Bolted timber joint · Yield theory · Yield strength · Ultimate strength

K. Sawata · M. Yasumura (✉)
Faculty of Agriculture, Shizuoka University, 836 Ohya, Shizuoka 422-8529, Japan
Tel. +81-54-238-4863; Fax +81-54-237-3028
e-mail: afmyasu@agr.shizuoka.ac.jp

Part of this paper was presented at the 52nd Annual Meeting of the Japan Wood Research Society, Gifu, April 2002; the Annual Meeting of Architectural Institute of Japan 2002, Ishikawa, August 2002; and the World Conference on Timber Engineering 2002, Shah Alam, Malaysia, August 2002

Introduction

According to the revision of Japanese building codes, the damage and ultimate limits of timber joints are of importance for the seismic design of timber structures. It is known that the shear strength of dowel-type joints subjected to a lateral force can be estimated using Johansen's yield theory.[1] In this theory, the embedding strength of wood and the yield moment of the dowel are governing properties for determining the shear strength of dowel-type joints.

The embedding strength of wood and the yield moment of the dowel depend on the method of evaluation. Some studies[2] have compared the yield and ultimate strengths of dowel-type joints calculated by the yield theory and compared them with the experimental results. However, the yield theory, based on the assumption that embedding of wood and bending of the dowel have stiff-plastic behavior,[3] does not consider the plastic behavior (e.g., hardening of the dowel and embedding of wood) after yielding. The embedding stress of wood and the bending moment of the dowel, corresponding to the yield and ultimate strengths of dowel-type joints, are important factors to be investigated when applying the yield theory.

The deformation and strength performance of dowel-type joints can be predicted by numerical analysis. It is known that finite element (FE) nonlinear analysis can approximate the load–slip behavior of dowel-type joints considering the elastoplastic behavior of wood and dowels. Foschi[4,5] carried out a nonlinear analysis based on the theory of a beam on an elastic foundation for some nailed joints. Tsujino and Hirai[6] conducted the FE analysis of bolted joints based on the theory of a beam on an elastic foundation. These studies reported that the prediction by nonlinear analysis agreed well with the experimental results. Furthermore, nonlinear analysis can examine the processes of embedding wood and yielding of the dowel.

This study examined appropriate application of the yield theory using FE nonlinear analysis, considering the elastoplastic behavior of both wood and bolt. The FE analysis was carried out on bolted timber joints with steel side

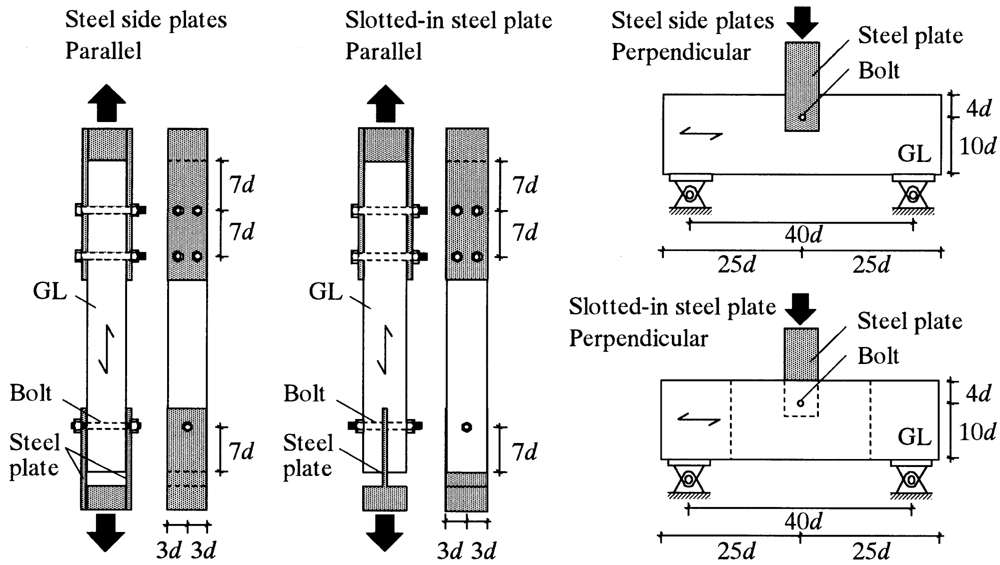

Fig. 1. Configuration of bolted joint test. *d*, bolt diameter; *GL*, glued laminated timber

plates and a slotted-in steel plate under lateral loads parallel and perpendicular to the grain. The bolt used in the bolted timber joints had three different strength and stress-strain curves. The embedding stress of wood under a bolt shank and the moment of bolt axis were obtained from FE analysis, and the method estimating the yield and ultimate strengths of bolted joints under lateral loads parallel and perpendicular to the grain using the yield theory was studied.

Materials and methods

Specimen

Double shear tests of bolted timber joints with steel side plates and a slotted-in steel plate were conducted on ezomatsu (*Picea jezoensis*), todomatsu (*Abies sachalinensis*), and spruce (*Picea abies*) glued laminated timbers. The specimens under lateral loads parallel and perpendicular to the grain consisted of three and nine laminas, respectively. The configurations of the specimens and their outlines are shown in Fig. 1 and Table 1, respectively. The grade of steel used for the bolt was SS400 according to the Japanese Industrial Standard.[9] The bolt was 16 mm in diameter (*d*), obtained from three lots with different strengths. In this study, bolts with 480, 530, and 640 MPa tensile ultimate strength are called types *L*, *M*, and *H*, respectively. The bolts were arranged parallel to the interface of the lamina. The thickness/bolt diameter ratios (*l*/*d*) were 4, 8, and 12. The edge and end distances of specimens under lateral loads parallel to the grain were 48 mm (3*d*) and 112 mm (7*d*), respectively. For the specimens under lateral loads perpendicular to the grain, the edge distance, height, and end distance of the specimens were 160 mm (10*d*), 224 mm (14*d*) and 400 mm (25*d*), respectively. The predrilled hole in the timber was 17 mm in diameter.

Table 1. Summary of bolted joint tests

Code	Loaded direction to the grain	Arrangement of steel plate to timber	Type of bolt	*l*/*d*
ASM 4	Parallel	Both sides	*M*	4
ASL 8	Parallel	Both sides	*L*	8
ASM 8	Parallel	Both sides	*M*	8
ASH 8	Parallel	Both sides	*H*	8
ASL 12	Parallel	Both sides	*L*	12
ASM 12	Parallel	Both sides	*M*	12
ASH 12[a]	Parallel	Both sides	*H*	12
ACM 4	Parallel	Central	*M*	4
ACL 8	Parallel	Central	*L*	8
ACM 8	Parallel	Central	*M*	8
ACH 8	Parallel	Central	*H*	8
ACL 12	Parallel	Central	*L*	12
ACM 12	Parallel	Central	*M*	12
ACH 12[a]	Parallel	Central	*H*	12
BSM 4	Perpendicular	Both sides	*M*	4
BSM 8	Perpendicular	Both sides	*M*	8
BSM 12	Perpendicular	Both sides	*M*	12
BCM 4	Perpendicular	Central	*M*	4
BCM 8	Perpendicular	Central	*M*	8
BCM 12	Perpendicular	Central	*M*	12

L, 480 MPa tensile strength; *M*, 530 MPa; *H*, 640 MPa; *l*/*d*, thickness/bolt diameter ratio
[a] From studies by Yasumura[7] and Shuto[8]

Double shear tests

Lateral loading tests were conducted on bolted timber joints with steel side plates and a slotted-in steel plate. Glued laminated timber and a steel plate 12 mm thick were connected with a bolt 16 mm in diameter. The bolt hole in the steel plate was 16.5 mm in diameter. For bolted joints with steel side plates, the clearance between the steel plate and the timber was 0.5 mm. The bolted joints with a slotted-in steel plate had no clearance between the steel plate and the timber. The bolted joints under lateral loads parallel and perpendicular to the grain were tested, respectively, in tension and bending, as shown in Fig. 1. The bending span of loading perpendicular to the grain was 640 mm. The slips between the steel plate and the timber were measured with two displacement transducers. Tests were carried out at a constant rate of 1.5 mm/min[10] and terminated when the slip became more than 20 mm or when the load decreased to 80% of the maximum load.

Finite element analysis

The nonlinear analysis of bolted timber joints was carried out using an FE model. The bolted joint was modeled as a rectangular beam on the nonlinear springs corresponding to the wooden foundation. The embedding stress–displacement relation for the spring was obtained from the results of embedding tests of wood.[11] The embedding behavior parallel to the grain was assumed to be perfect elastoplastic; that is, it behaves linearly up to a embedding yield strength and then is constant after the yielding. The embedding behavior perpendicular to the grain was approximated to be a bilinear model that behaves as a linear increase up to the yielding and continuously increases after yielding. The embedding model parallel and perpendicular to the grain is shown in Fig. 2. The elastoplastic behavior of the bolt was assumed to be a trilinear model based on the tensile tests of the steel bar.[12] The tensile model of the bolt is shown in Fig. 3. The rectangular cross section of beam had the equivalent plastic section modulus and the geometrical moment of inertia of the bolt with the circular cross section. The width and height of the beam corresponding to the shank 16 mm in diameter were 13.7 mm and 14.1 mm, respectively. In the experiment with bolted joints that had steel side plates, part of screw thread touched the bolt hole boundary of the steel plate. Therefore, the width and height of the beam corresponding to the screw thread were reduced, respectively, to 11.8 mm and 12.2 mm, considering the smallest diameter of the screw thread (13.8 mm).[13] The bolt head was clamped during the modeling of the bolted joints with steel side plates. With the slotted-in steel plate, the bolt head was free to rotate. The boundary conditions of the FE model are shown in Fig. 4. The numerical computations were performed with the FE codes CASTEM 2000.[14] The stiffness matrix for the beam element in a local coordinate system with an axial force was used in this study.[15]

Results and discussion

Evaluation method

The initial stiffness, yield strength, and ultimate strength were obtained from the load–slip relation in the experiment and the FE analysis. The initial stiffness parallel to the grain was determined by the line that goes through the points on the curve corresponding to 10% and 40% of the maximum load up to 15 mm slip. Perpendicular to the grain, the initial stiffness was obtained from the points on the curve corresponding to 10% and 30% of the maximum load up to 15 mm slip. The yield strength was evaluated by the 5% offset method according to ASTM D5652.[16] With this method the original line defining the initial stiffness is moved 5% of bolt diameter parallel with the original line toward the X-direction, and the intersection of this line and the load-slip curve defines the yield strength. The ultimate strength was obtained from the maximum load up to 15 mm slip according to EN26891.[17] Tables 2 and 3 show the results obtained from the analysis and the experiments, respectively.

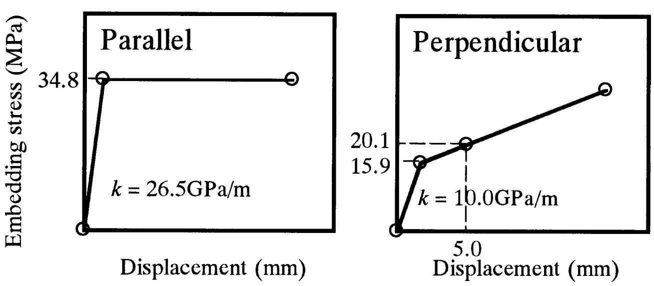

Fig. 2. Embedding model of wood for finite element (FE) analysis. *k*, embedding stiffness

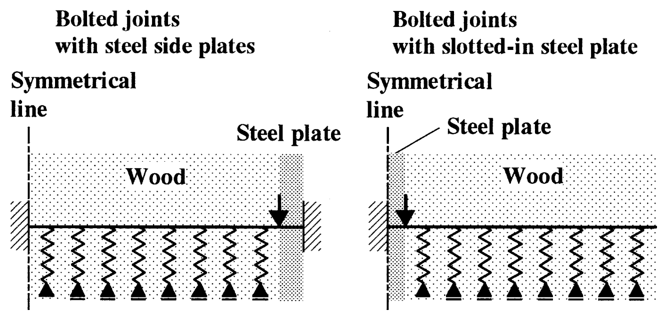

Fig. 4. Boundary conditions of the FE model

Fig. 3. Tensile model of the bolt for FE analysis

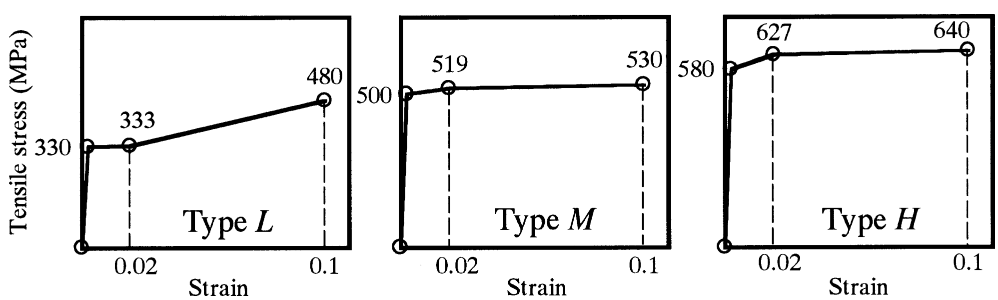

Table 2. Results of finite element analysis

Code	PW		PB1		PB2		Py (kN)	Dy (mm)	Pu (kN)	Du (mm)
	P (kN)	δ (mm)	P (kN)	δ (mm)	P (kN)	δ (mm)				
ASM 4	35.1	1.36	–	–	–	–	36.8	2.22	36.8	15.0
ASL 8	34.9	1.36	29.4	0.940	39.3	2.17	38.9	1.89	53.5	15.0
ASM 8	43.9	1.36	34.2	0.974	45.2	1.47	48.6	2.14	52.5	15.0
ASH 8	45.6	1.36	36.6	1.01	50.2	1.64	53.7	2.28	57.4	15.0
ASL 12	34.7	1.36	24.5	0.870	41.1	3.13	40.1	2.16	51.8	15.0
ASM 12	38.1	1.36	27.5	0.862	50.1	2.69	48.0	2.24	52.5	15.0
ASH 12	39.7	1.36	29.5	0.887	53.1	2.89	52.1	2.36	56.8	15.0
ACM 4	34.5	1.36	–	–	–	–	36.8	2.25	36.8	15.0
ACL 8	30.0	1.36	26.2	1.11	–	–	35.1	1.99	49.0	15.0
ACM 8	35.7	1.36	30.0	0.965	–	–	39.5	1.96	45.1	15.0
ACH 8	38.8	1.36	33.9	1.05	–	–	43.2	2.07	47.6	15.0
ACL 12	33.8	1.36	31.7	1.24	49.2	5.54	44.8	2.42	58.1	15.0
ACM 12	38.7	1.36	32.2	1.01	–	–	45.3	2.11	55.2	15.0
ASH 12	41.1	1.36	35.7	1.08	–	–	48.0	2.19	56.4	15.0
BSM 4	17.0	1.97	–	–	–	–	18.2	2.80	35.0	15.0
BSM 8	29.9	1.97	29.0	1.88	36.0	3.50	35.0	3.06	45.5	15.0
BSM 12	28.1	1.97	20.1	1.21	33.1	2.93	32.6	2.77	44.9	15.0
BCM 4	17.0	1.97	–	–	–	–	18.1	2.80	35.0	15.0
BCM 8	25.5	1.97	24.6	1.78	–	–	25.9	2.56	37.6	15.0
BCM 12	25.0	1.97	22.1	1.54	–	–	27.0	2.54	43.5	15.0

PW, first yielding of wood; PB1, yielding of bolt at the first position; PB2, yielding of bolt at the second position; P, load; δ, slip; Py, yield strength; Dy, yield displacement; Pu, ultimate strength; Du, ultimate displacement

Table 3. Yield and ultimate strengths calculated from the experiment and the yield theory

Code	ρ (kg/m^3)	Experiment		Yield theory	
		Py (kN)	Pu (kN)	Py (kN)	Pu (kN)
ASM 4	407	32.4	34.5	35.6	35.6
ASL 8	410	34.7	52.2	44.8	47.5
ASM 8	424	39.0	55.8	55.1	55.8
ASH 8	429	37.7	60.1	59.4	61.9
ASL 12	379	32.1	48.8	44.8	47.5
ASM 12	463	40.5	65.1	55.1	55.8
ASH 12	440	37.5	66.3	59.4	61.9
ACM 4	401	29.8	33.4	35.6	35.6
ACL 8	364	41.3	52.6	39.0	40.2
ACM 8	372	35.3	53.9	43.6	43.9
ACH 8	407	37.7	60.3	45.7	47.0
ACL 12	420	45.8	61.3	44.8	47.5
ACM 12	395	38.5	56.2	54.0	54.3
ACH 12	440	41.0	66.6	55.5	56.4
BSM 4	438	13.9	25.7	16.3	24.4
BSM 8	462	23.9	53.5	32.6	46.1
BSM 12	464	29.2	62.8	37.3	46.1
BCM 4	412	14.3	28.5	16.3	24.4
BCM 8	457	26.8	59.6	26.7	34.2
BCM 12	447	26.9	61.5	29.6	40.1

ρ, density; Py, yield strength; Pu, ultimate strength

Load–slip relation

Load–slip relations up to 15 mm displacement were obtained from the experiment and FE analysis. The load–slip relations of bolted timber joints with bolt type *M* are shown in Fig. 5. The intersection of the initial stiffness on the load–slip curve and X-axis is moved to the point of origin. On the whole, the initial stiffness obtained by analysis was higher than that obtained from the experiment. However, analysis of the bolted joints with a slotted-in steel plate predicted the experimental results better than that of the bolted joints with steel side plates. This may be caused by neglecting the bolt hole clearance in the analysis, and the effect of clearance may appear more clearly on the bolted joints with steel side plates than those with slotted-in steel plate. The ultimate strengths of bolted joints under lateral loads parallel to the grain obtained by analysis agreed well with those obtained from the experiment. Perpendicular to the grain, the ultimate strength obtained by analysis was about 30% smaller than the experimental results when the *l*/*d* ratios were 8 and 12. Figure 5 also shows the load for first yielding of nonlinear springs (PW) and the loads for yielding of the bolt at the first ($PB1$) and second ($PB2$) positions obtained from the analysis. When the *l*/*d* ratios were 8 and 12, the first yielding of the bolt always occurred at the boundary between the steel plate and the wood, and the second appeared on inner side of the main member (Fig. 6).

Shear strength calculated by yield theory

With the yield theory, the bolted timber joints with the steel side plates and slotted-in steel plate have two and three yield modes, respectively. A symmetrical single joint in double shear is considered. The yield mode depends on the hypothesis that the bolt remains straight during yielding, and the yield moment of the bolt is reached at one or two points. When the bolt has one or two yield moments, equilibrium equations for bolted joints with steel side plates and a slotted-in steel plate, as seen below.

When the bolt has one yield point (bolted joints with slotted-in steel plate):

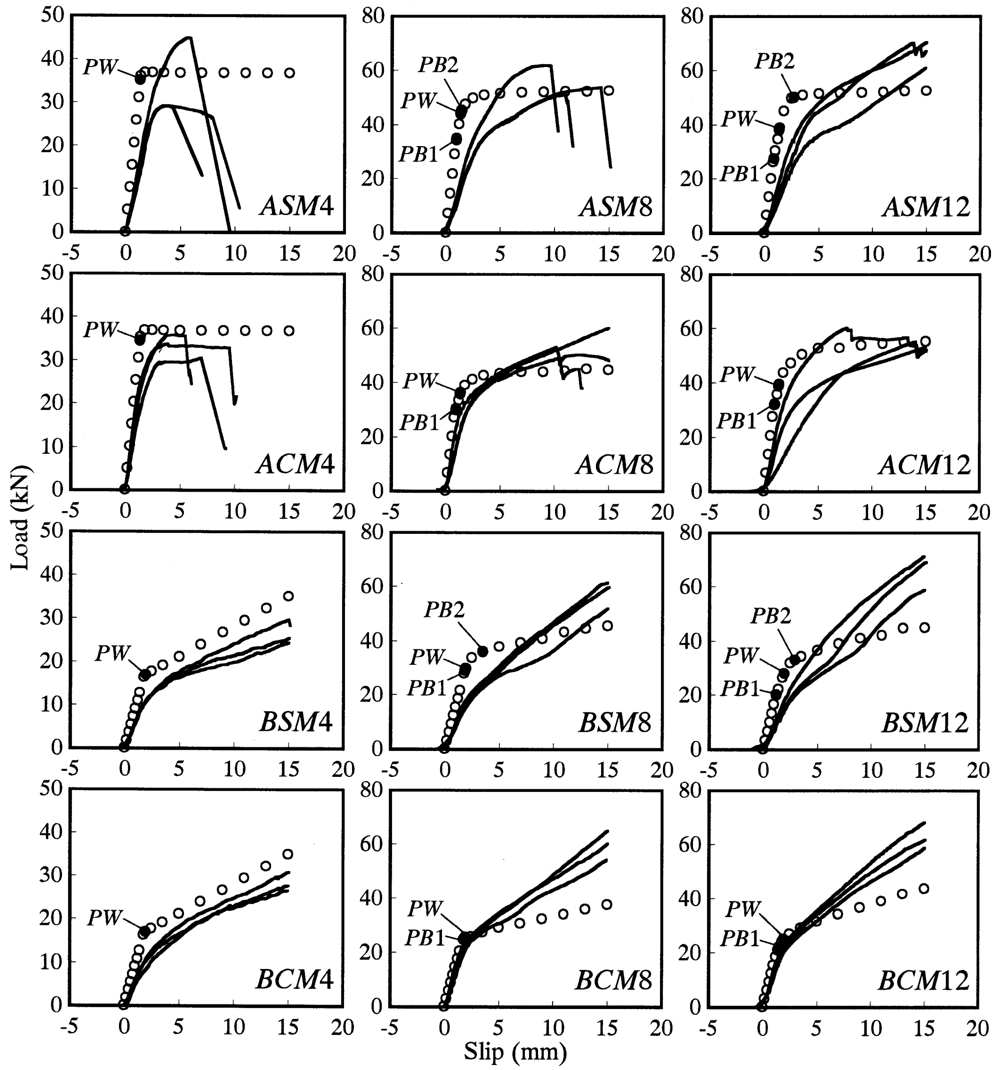

Fig. 5. Load–slip diagrams for bolted joints subjected to lateral force. *Solid lines*, experiment; *circles*, FE analysis; *PW*, first yielding of wood; *PB*1, yielding of the bolt at the first position; *PB*2, yielding of the bolt at the second position

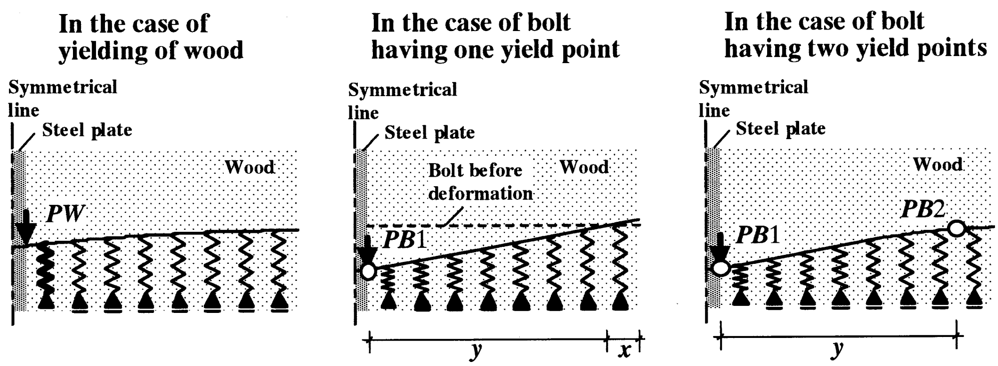

Fig. 6. Yield conditions of wood and bolt in bolted joints with slotted-in steel plate

$$\frac{Fy}{2} = fe \cdot (y - x) \cdot d$$

$$My = \frac{1}{2} fe \cdot (y - x)^2 \cdot d - fe \cdot x^2 d \quad (1)$$

$$\frac{l}{2} = y + x$$

When the bolt has two yield points (bolted joints with steel side plates and slotted-in steel plate):

$$\frac{Fy}{2} = fe \cdot y \cdot d$$

$$My = \frac{1}{2} fe \cdot y^2 \cdot d - My \quad (2)$$

where *Fy* is the shear strength of bolted joints (N), *fe* is the embedding strength of wood (MPa), *My* is the yield moment of bolt (Nmm), *l* is the thickness of the wood (mm), *d* is the bolt diameter (mm), and x and y are the lengths as shown in Fig. 6.

The shear strength of bolted joints according to the yield theory is expressed as follows from Eqs. (1) and (2).

Bolted timber joints with steel side plates:

$$Fy = min \cdot \begin{cases} fe \cdot l \cdot d \\ 4\sqrt{fe \cdot My \cdot d} \end{cases} \quad (3)$$

Bolted timber joints with slotted-in steel plate:

$$Fy = min \cdot \begin{cases} fe \cdot l \cdot d \\ fe \cdot l \cdot d\left(\sqrt{2 + \dfrac{16My}{fe \cdot l^2 \cdot d}} - 1\right) \\ 4\sqrt{fe \cdot My \cdot d} \end{cases} \quad (4)$$

The embedding strength showed significant correlation with the density.[11] Therefore, the embedding yield and ultimate strengths of the wood were estimated from the density of the lamina used for the bolted joint tests. In the case of bolted joints under lateral loads parallel to the grain, the mean density of the lamina was 410 kg/m^3. The embedding yield and ultimate strengths parallel to the grain were assumed to be 34.8 MPa based on the maximum load up to 5 mm displacement.[18] When perpendicular to the grain, the mean density of the lamina was 430 kg/m^3. The embedding yield strength was obtained by the 5% offset method.[16] The embedding ultimate strength perpendicular to the grain was obtained by assuming a bilinear model with the same energy dissipated up to 15 mm displacement. The embedding yield and ultimate strengths perpendicular to the grain were 15.9 and 23.8 MPa, respectively. The yield and ultimate moments of the bolt were calculated from the yield and ultimate strengths obtained by tensile tests on the bolt using a plastic section modulus, respectively. The yield strength was stress having 0.2% permanent set.[19] The ultimate strength of the bolt was obtained by assuming a bilinear model with the same energy dissipated up to 0.1 strain. The yield strength and yield moment of bolt types L, M, and H were 330, 500, and 580 MPa and 225, 341, and 396 Nm, respectively. The ultimate strength and ultimate moment of bolt types L, M, and H were 370, 510, and 630 MPa and 253, 348, and 430 Nm, respectively. In this study the shear strength of bolted joints calculated from the yield theory using the embedding yield strength of wood and the yield moment of the bolt was assumed to be the yield strength of the bolted joints. That, calculated by the yield theory from the embedding ultimate strength of wood and the ultimate moment of the bolt, was assumed to be the ultimate strength of the bolted joints. The result calculated from the yield theory is shown in Table 3.

Embedding stress under the bolt shank

The embedding stress distribution of wood under the bolt shank, corresponding to the yield and ultimate strengths of the bolted timber joints, was obtained from the FE analysis. Figure 7 shows the embedding stress in bolted joints with bolt type M and l/d ratios of 8 and 12. Figure 7 also shows the embedding stress calculated from the yield theory. The distribution of embedding stress in the yield theory was obtained from the values of x and y in Eqs. (1) and (2). In the case of bolted joints under lateral loads parallel to the grain, the plastic area of embedding obtained from the analysis approximated that calculated by the yield theory, especially regarding ultimate strength. This means that a large part of the wooden foundation exhibits still elastic behavior when bolted joints attain yield strength, and the stiff-plastic assumption of yield theory can be satisfied in the ultimate state. In the case of bolted joints under lateral loads perpendicular to the grain, the embedding stress of wood shows a continuous increase after the yielding of the wood, although the embedding behavior is assumed to be stiff-plastic behavior in the yield theory. Therefore, the embedding behavior in bolted joints under lateral loads perpendicular to the grain in the analysis did not show good approximation with that seen by the yield theory.

Bending moment of the bolt axis

The bending moment of the bolt axis corresponding to the yield and the ultimate strengths of bolted timber joints was obtained by the FE analysis. Figure 8 shows the bending moment of bolt type M on bolted joints with steel side plates. When l/d ratios were 8 and 12, distances from a symmetrical line to the boundary between the steel plate and the wood were, respectively, 64 and 96 mm in the bolted joints with steel side plates. The yielding of the bolt at the first and second positions are also shown; that is, the first yielding of the bolt appeared at the boundary between the steel plate and the wood, and the second appeared at the inner side of the main member. The yielding position with the largest strain at the inner side of the main member moved toward the steel plate as the load increased. For bolted joints under lateral loads parallel to the grain, the distance between the first and second positions of yielding by the bolt was close to the effective embedding length (y) obtained from Eq. (2) on the ultimate strength of bolted joints, as shown in Figs. 7 and 8.

Yield and ultimate strengths

The yield strength of bolted timber joints was compared with the maximum values PW, $PB1$, and $PB2$ based on the FE analysis, as shown in Fig. 9. Regardless of the joint type and the loading direction, the maximum value agreed with the yield strength obtained from the analysis. This means that the yielding of bolted joints corresponds to the state where both wood and bolt yield.

The yield and ultimate strengths of bolted joints obtained from the experiment and analysis were compared with those calculated from the yield theory, as shown in Fig. 10. The yield and the ultimate strengths obtained

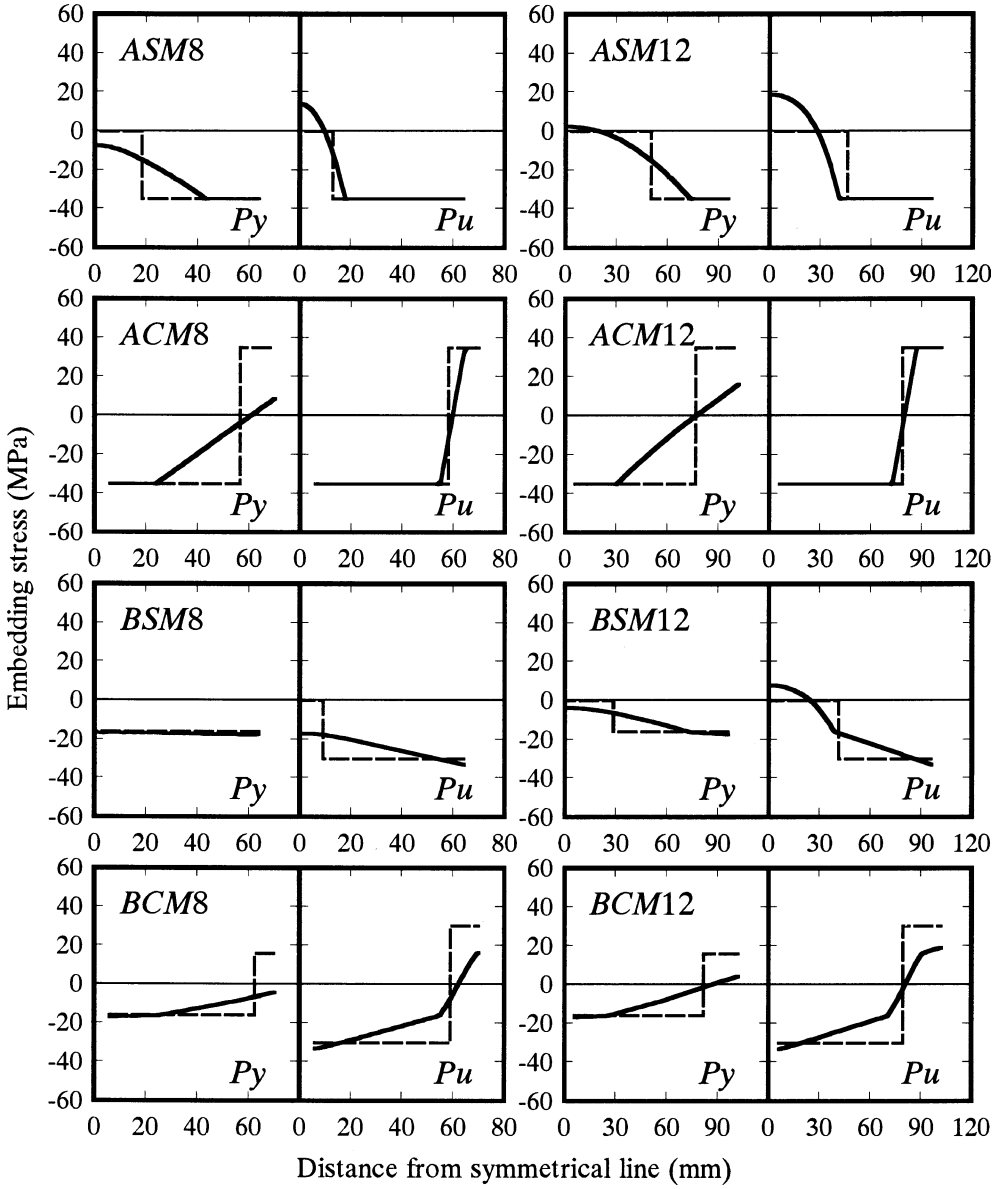

Fig. 7. Embedding stress distribution under the bolt shank. *Py*, yield strength; *Pu*, ultimate strength; *solid line*, results of FE analysis; *broken line*, results calculated from yield theory

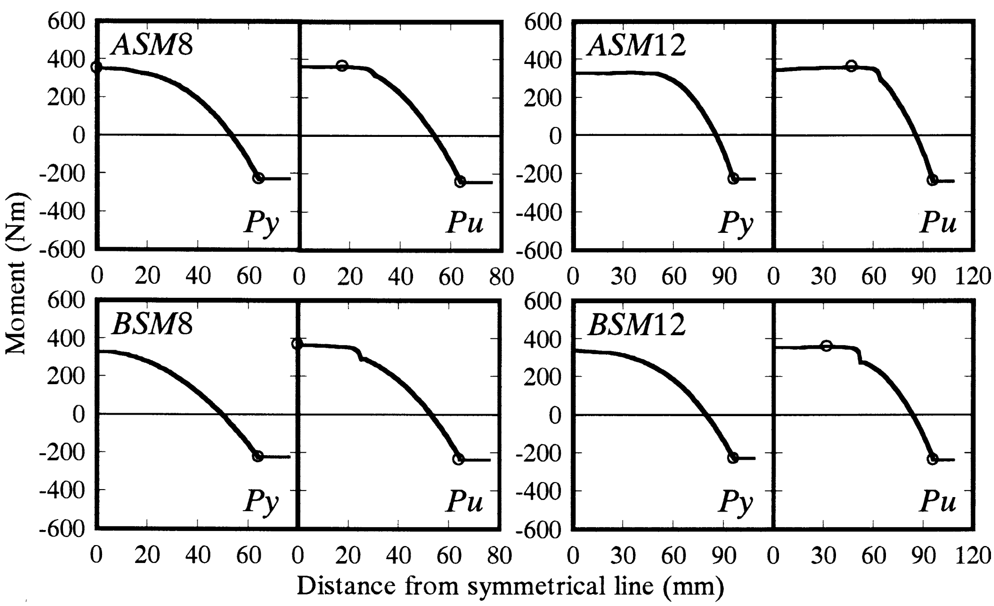

Fig. 8. Moment distribution in bolt axis. *Py*, yield strength; *Pu*, ultimate strength; *solid line*, results of FE analysis; *open circles*, yielding positions with largest strain

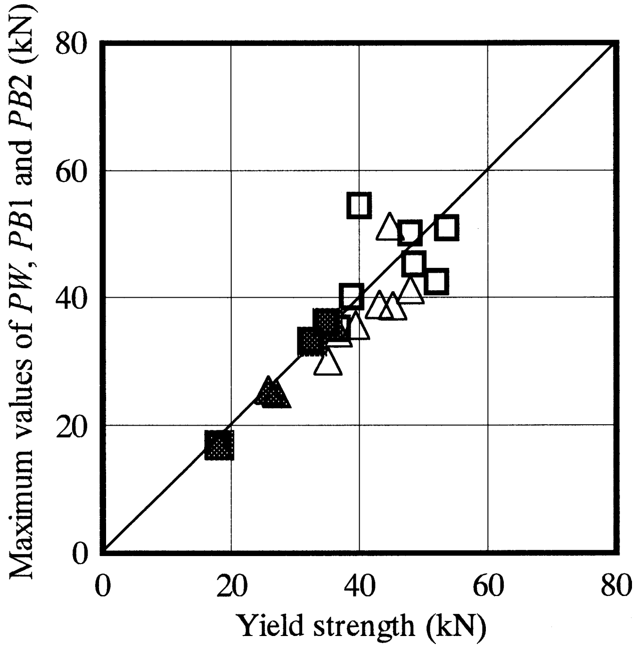

Fig. 9. Relations between maximum values among *PW*, *PB*1, and *PB*2 and yield strength obtained by FE analysis. *Open squares*, joints parallel to the grain with steel side plates; *open triangles*, joints parallel to the grain with slotted-in steel plate; *filled squares*, joints perpendicular to the grain with steel side plates; *filled triangles*, joints perpendicular to the grain with slotted-in steel plate

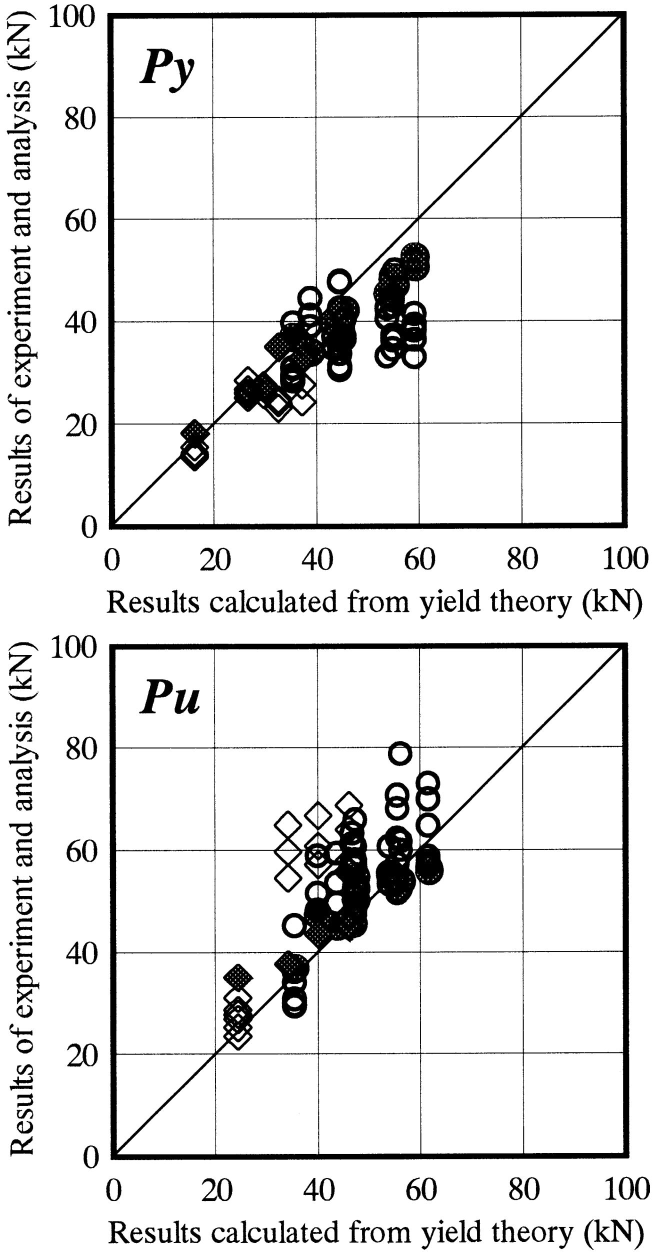

Fig. 10. Comparison of results of the experiment and FE analysis with results calculated based on the yield theory. *Py*, yield strength; *Pu*, ultimate strength; *open circles*, experimental results parallel to the grain; *open diamonds*, experimental results perpendicular to the grain; *filled circles*, results parallel to the grain by FE-analysis; *filled diamonds*, results perpendicular to the grain by FE analysis

from the analysis agreed well with those calculated from the yield theory. The experimental yield strength was close to the yield strength calculated from the yield theory, and the experimental ultimate strength was 0%–74% larger than the ultimate strength calculated from the yield theory.

Conclusions

Based on the FE nonlinear analysis of bolted timber joints, it was found that the yielding of the bolt first appears at the boundary between the steel plate and the wood and then on the inner side of the main member. The maximum values among the loads for first yielding of the nonlinear spring and yielding of the bolt at the first and second positions approximates the yield strength evaluated by the 5% offset method from the load–slip relations in the analysis.

The yield strength of bolted joints calculated by the yield theory from the embedding yield strength of wood and the yield moment of the bolt agrees well with the yield strengths of bolted joints evaluated by the 5% offset method from the load–slip relations in the experiment and analysis. The ultimate strength of bolted joints calculated by the yield theory from the embedding ultimate strength of wood and the ultimate moment of the bolt is close to the ultimate strength of bolted joints evaluated by the maximum load up to 15 mm slip in the analysis. The ultimate strength for the yield theory underestimates the ultimate strength of bolted joints evaluated by the maximum load up to 15 mm slip in the experiment.

The FE nonlinear analysis in this study showed that the yield and the ultimate strengths of bolted timber joints can be estimated by the yield theory when the appropriate embedding strength of wood and the bending moment of bolt are applied.

References

1. Johansen KW (1949) Theory of timber connections. Publication 9. International Association of Bridge and Structural Engineering, Bern, pp 249–262
2. Yasumura M, Murota T, Sakai H (1987) Ultimate properties of bolted joints in glued-laminated timber. In: Proceedings of the CIB-W18 meeting, Dublin, paper 20-7-3
3. Larsen HJ (1974) The yield load of bolted and nailed joints. Report R.52. Structural Research Laboratory, Technical University of Denmark, Lyngby
4. Foschi RO (1974) Load-slip characteristics of nails. Wood Sci 7(1):69–76
5. Foschi RO (1977) Load-slip characteristics for connections with common naols. Wood Sci 9(3):118–123
6. Tsujino T, Hirai T (1983) Nonlinear load-slip relationship of bolted wood-joints with steel side-members. I. Numerical analysis based upon a finite element method (in Japanese). Mokuzai Gakkaishi 29:833–838
7. Yasumura M (1998) Mechanical properties of dowel type joints under reversed cyclic lateral loading. In: Proceedings of the CIB-W18 meeting, Savonlinna, paper 31-7-1
8. Shuto T (1999) Mechanical properties of bolted timber joints subjected to reversed cyclic lateral loads (in Japanese). Master's dissertation, Shizuoka University
9. Japanese Industrial Standard (1987) Rolled steel for general structure (in Japanese). JIS G 3101
10. Architectural Institute of Japan (1995) Standard for structural design of timber structures (in Japanese). Architectural Institute of Japan, Tokyo
11. Sawata K, Yasumura M (2002) Determination of embedding strength of wood for dowel-type fasteners. J Wood Sci 48:138–146
12. Yasumura M, Sawata K (2000) Determination of yield strength and ultimate strength of dowel-type timber joints. In: Proceedings of CIB-W18 meeting, Delft, paper 33-7-1
13. Japanese Industrial Standard (1982) Metric coarse screw threads (in Japanese). JIS B 0205
14. Yasumura M, Daudeville L (1996) Fracture analysis of bolted timber joints under lateral force perpendicular to the grain. Mokuzai Gakkaishi 42:225–233
15. Ketter LR, Lee CG, Prawel PS Jr (1979) Structural analysis and design. McGraw-Hill Kogakusha, Tokyo, pp 726–741
16. American Society for Testing and Materials (1995) Standard test methods for bolted connections in wood and wood-based products. ASTM D-5652. ASTM, West Conshohocken, PA, USA
17. European Committee for Standardization (1991) EN26891: timber structures—joints made with mechanical fasteners: general principles for the determination of strength and deformation characteristics. ECS, Brussels
18. European Committee for Standardization (1993) EN383: Timber structures—test methods: determination of embedding strength and foundation values for dowel type fasteners. ECS, Brussels
19. Japanese Industrial Standard (1998) Method of tensile test for metallic materials (in Japanese). JIS Z 2241