J Wood Sci (2007) 53:204–210
DOI 10.1007/s10086-006-0842-z

ORIGINAL ARTICLE

**Ali Awaludin · Watanachai Smittakorn · Takuro Hirai
Toshiro Hayashikawa**

Bearing properties of *Shorea obtusa* beneath a laterally loaded bolt

Received: January 18, 2006 / Accepted: August 30, 2006 / Published online: December 21, 2006

Abstract Empirical equations to determine the bearing strength have been proposed by many researchers and design standards. Because these equations have been developed mainly based on test results of softwood species, it is a matter of great importance (to ASEAN structural engineers) to verify the applicability of these equations for tropical hardwood species, which are commonly used in many ASEAN countries. In this study, wood specimens of *Shorea obtusa* (a tropical hardwood species) were used and the bearing test under full-hole configuration was carried out for five different loading angles to the grain. The bearing stress–embedment curve obtained from the test was approximated by a linear elastic–plastic diagram indicating the initial and final stiffness of the curve. Testing showed that the average bearing strength parallel to the grain was 7.25% lower than the prediction given in Eurocode 5. The bearing strength perpendicular to the grain evaluated based on bearing load at initial cracking was substantially different from any predictions given by previous studies or design standards. It was also found that the bearing strength and initial stiffness from the bearing stress–embedment curve for loading at intermediate angles to the grain could be satisfactorily predicted with Hankinson's formula.

Key words Bearing strength · Initial stiffness · Loading angle to the grain · *Shorea obtusa*

A. Awaludin (✉) · T. Hayashikawa
Laboratory of Bridge and Structural Design Engineering, Graduate School of Engineering, Hokkaido University, Kita 13 Nishi 8, Kita-ku, Sapporo 060-8628, Japan
Tel. +81-11-706-6170; Fax +81-11-757-8159
e-mail: awaludin@eng.hokudai.ac.jp

W. Smittakorn
Graduate School of Engineering, Chulalongkorn University, Bangkok 10330, Thailand

T. Hirai
Graduate School of Agriculture, Hokkaido University, Sapporo 060-8589, Japan

Introduction

Tropical hardwood species are, in most ASEAN (Association of Southeast Asian Nations) countries, usually used for many types of structures such as residential houses, historical buildings, bridges, and other structures. The mechanical properties of tropical hardwood species are generally different from those of softwood species.[1,2] For instance, the specific gravity of tropical hardwood species is significantly higher than that of softwood species. Moreover, the grain orientation of tropical hardwood species is not as easy to determine visually as it is in softwood species. When the strength of a tropical timber connection is analyzed by using yield theory,[3] the bearing strength of the wood has to be known previously. Bearing strength can be easily evaluated from empirical equations given by previous studies or standards. However, the calculated bearing strength might be questionable because the equations were developed mainly based on test data of softwood species. This study investigated the bearing properties of *Shorea obtusa*, which is one of most popular tropical hardwood species in ASEAN countries, and examined whether the equations proposed by previous researchers and standards well predict the test results. Finally, the findings of this study will allow the use of yield theory to be simplified and utilization of tropical hardwood species to become more efficient.

Literature review

Previous works regarding the bearing strength of wood concluded that the diameter of fasteners, specific gravity, and loading angle to the grain were significant parameters.[4–9] Empirical equations to determine the bearing strength of timber were proposed based on the experimental data. However, because the bearing resistance is very sensitive to specimen dimensions and test configurations, trials to validate the equations are consequently required. Two types of test methods commonly used to evaluate the bearing

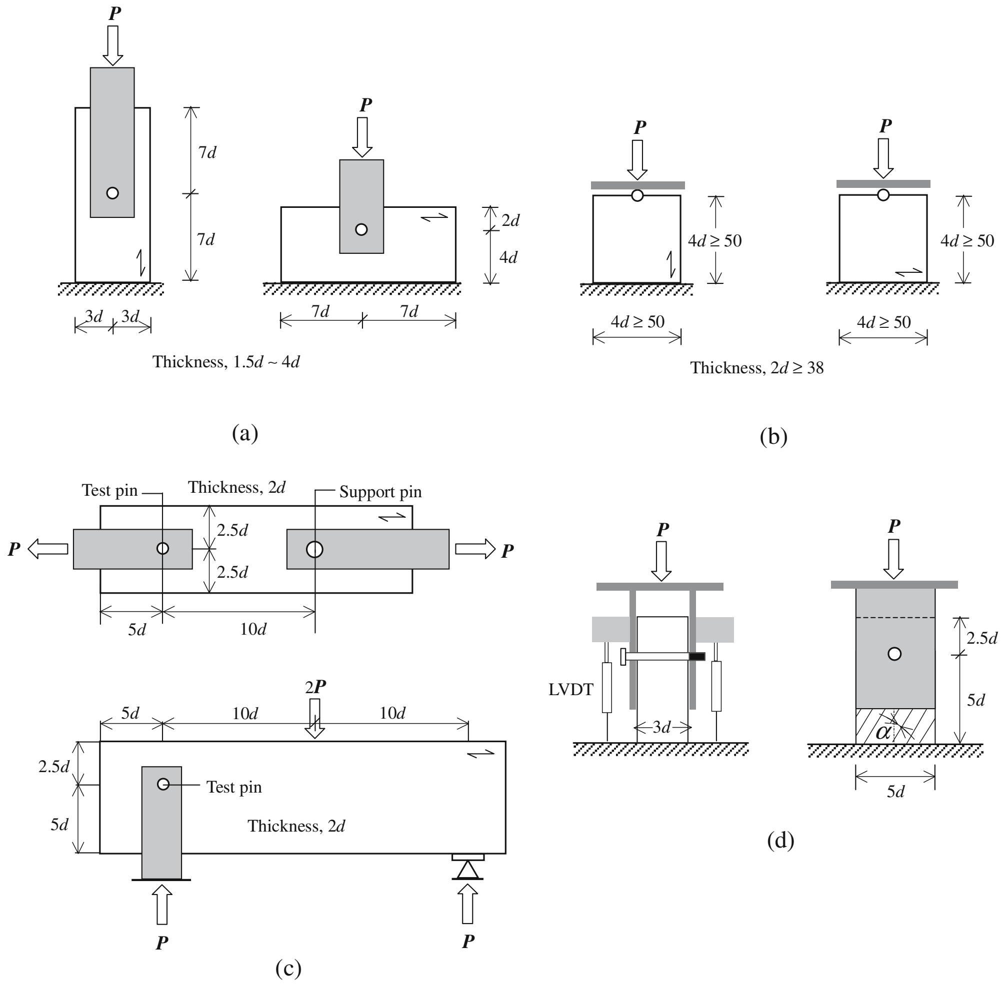

Fig. 1a–d. Several bearing test configurations. **a** Test configuration of Eurocode 5; **b** half-hole test of National Design and Specification (NDS); **c** Hirai's test configuration;[8] and **d** full-hole test adopted in this study. Dimensions are given in millimeters. *d*, Bolt diameter; α, loading angle to the grain; *LVDT*, linear variable differential transducer. Grain orientation is indicated by *double-ended half arrows*

strength are the full-hole and half-hole tests. The full-hole test proposed by Whale and Smith,[4] and accepted by Eurocode 5,[10] is illustrated in Fig. 1a. Equations 1 and 2 were proposed to determine the bearing strength for loading parallel ($F_{e//}$) and perpendicular to the grain ($F_{e\perp}$), respectively. In the equations, the bolt diameter (d) is expressed in millimeters and the oven-dry specific gravity of wood (G) is unitless.

$$F_{e//} = 82(1-0.01d)G \qquad (\mathrm{N/mm^2}) \tag{1}$$

$$F_{e\perp} = \frac{82(1-0.01d)G}{0.9+0.015d} \qquad (\mathrm{N/mm^2}) \tag{2}$$

A series of tests under full-hole configuration was carried out by Ehlbeck and Werner[5] to determine the bearing strength of European softwood, and some European and Asian hardwood species. The species used and their average specific gravities were: *Picea abies*, 0.422; *Fagus sylvatica*, 0.714; *Quercus robur* and *Quercus petraea*, 0.733; *Tectona grandis*, 0.652; *Intsia* spp., 0.804; *Afzelia* spp., 0.714; *Lophira alata*, 1.074. They proposed Eq. 3 to determine the bearing strength for any loading angle to the grain (α) where k_{90} was equal to 1.35 + 0.015d for softwood species and equal to 0.9 + 0.015d for hardwood species.

$$F_{e\alpha} = \frac{82(1-0.01d)G}{\left(k_{90}\sin^2\alpha + \cos^2\alpha\right)} \qquad (\mathrm{N/mm^2}) \tag{3}$$

The half-hole test as shown in Fig. 1b was proposed by Soltis and Wilkinson,[6] and Wilkinson,[7] and it was adopted in the *National design specification for timber construction* (NDS).[11] From bearing test results of some commercial wood species (Douglas fir, southern pine, spruce-pine fir, Sitka spruce, red oak, yellow poplar, aspen; average specific gravity: 0.36–0.58), Eqs. 4 and 5 were suggested to estimate the bearing strength for the loading angle set parallel and perpendicular to the grain, respectively. When the wood specimen is not loaded in the directions parallel or perpendicular to the grain, Hankinson's formula (Eq. 6) can be applied where m is a property-dependence constant.

$$F_{e//} = 77.25G \qquad (\mathrm{N/mm^2}) \tag{4}$$

$$F_{e\perp} = 212G^{1.45}d^{-0.5} \qquad (\mathrm{N/mm^2}) \tag{5}$$

$$F_{e\alpha} = \frac{F_{e//}F_{e\perp}}{F_{e//}\sin^m\alpha + F_{e\perp}\cos^m\alpha} \qquad (\mathrm{N/mm^2}) \tag{6}$$

Hirai[8] proposed Eqs. 7 and 8 to determine the bearing strength required in approximation of bearing stress–embedment curves for parallel and perpendicular loading angles to the grain, respectively. In Eq. 8, d_h denotes the diameter of the bolt hole expressed in millimeters. Hirai's empirical equations were based on test data of some wood species (spruce, hemlock, and Douglas fir) with specific gravity varying from 0.38 to 0.55 under the test configuration shown in Fig. 1c.

$$F_{e//} = 91.44G - 11.16 \qquad (\mathrm{N/mm^2}) \tag{7}$$

$$F_{e\perp} = (25.04G + 1.35)(d_h/10)^{-0.4} \qquad (\mathrm{N/mm^2}) \tag{8}$$

Hirai[9] also carried out bearing tests under several test configurations that were similar to those proposed by Whale and Smith,[4] Soltis and Wilkinson,[6] and Wilkinson.[7] Hirai found acceptable agreement among the test results only for loading parallel to the grain.

Materials and methods

Wood of *Shorea obtusa* and 12.4-mm-diameter bolts were used in this study. This wood has been commercially known by some popular names: balau or taeng among ASEAN countries. The specific gravity of this wood at 15% moisture content varies from 0.83 to 1.04.[12] Due to high density and high resistance to decay when fully exposed to the weather, this wood species has been widely used for many types of heavy engineering constructions such as framing, roofing, and decking systems. Wood specimens were purchased at a local lumber retailer and were kept inside the testing laboratory for a few weeks before testing. No specific seasoning process was applied to adjust the moisture content of the wood specimens.

A double-shear bearing test shown in Fig. 1d was conducted in compression at a constant displacement rate of 1.2 mm/min. The magnitude of compressive load was acquired by a 100-kN load cell, and embedment of the bolt into the wood was continuously measured by using two linear variable differential transducers (LVDTs). The bearing displacement measurement shown in Fig. 1d might also include compressive deformation of the wood specimen. However, previous research has shown that the compressive deformation is negligible in comparison with the bearing embedment of fastener into wood specimen.[13,14] During the test, the load–embedment curve was drawn based on the current data measurement, and wood splitting was observed visually.

The loading angle to the grain varied in five angles: 0°, 30°, 45°, 60°, and 90°. The bearing test of loading parallel or perpendicular to the grain consisted of six wood specimens, while only three wood specimens were prepared for the bearing test of each intermediate loading angle to the grain. A full-hole test configuration similar to Eurocode 5 was conducted with a bolt-hole diameter of 13 mm and steel gusset plate of 4 mm in thickness. Because the number of replicates of each loading angle to the grain was small, the wood specimens were cut from the same wood piece based on a matched samples technique as shown in Fig. 2. The

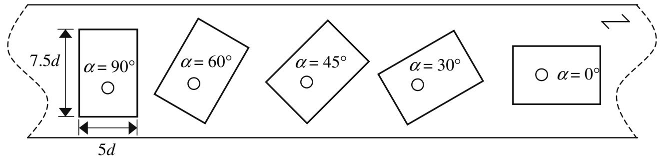

Fig. 2. Wood specimen fabrication

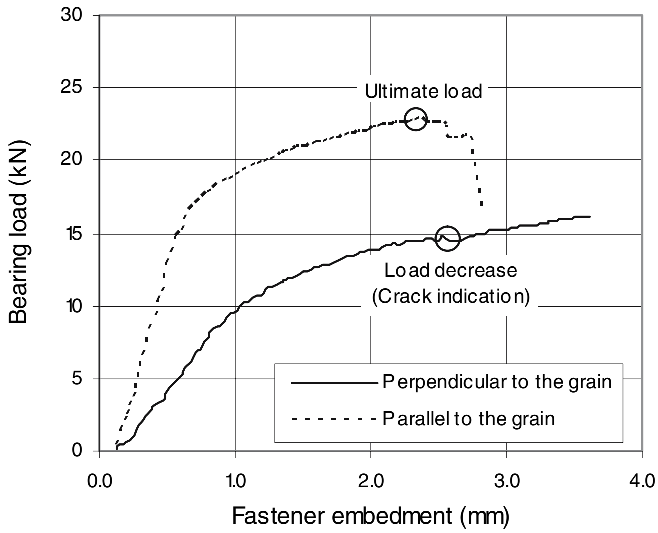

Fig. 3. Experimental load–embedment curves of loading parallel and perpendicular to the grain

dimensions of wood specimens used in this study were smaller than those of the Eurocode 5 as shown in Fig. 1d, because of size restrictions of the wood pieces that we used. This ensured that all wood specimens of different loading angle to the grain could be fabricated from the same wood piece. The bearing strength was determined as the bearing load divided by the projected area of the bolt. Moisture content and specific gravity based on oven-dry weight and volume of specimens were measured by using small pieces cut from wood specimens used in the bearing tests.

Results and discussion

From 21 wood specimens, it was found that the moisture content of the specimens varied from 12.35% to 17.51% with an average of 14.17%. The specific gravity obtained from the same wood specimens ranged from 0.82 to 0.90 with an average value of 0.86. The average value of oven-dry specific gravity was used to estimate the bearing strength in directions both parallel and perpendicular to the grain. The typical load–embedment curves of loading parallel and perpendicular to the grain obtained from the experiment are shown in Fig. 3. Wood specimens loaded parallel to the grain failed after reaching their maximum load, so that the load used for bearing strength evaluation was always the highest applied load. For the specimens loaded perpendicular to the grain, the failure mechanism was completely dif-

Table 1. Estimated and experimental bearing strength

	NDS[a,b] (Eq. 4 or 5)	Eurocode 5[a,c] (Eq. 1 or 2)	Hirai[a,d] (Eq. 7 or 8)	Experiment[e]		
				Average	Range	SD
$F_{e//}$ (N/mm^2)	66.44	61.78	67.48	57.30	55.65–60.25	1.67
$F_{e\perp}$ (N/mm^2)	48.38	56.88	20.60	34.37	31.53–37.22	2.39

NDS, National design specification for timber construction; $F_{e//}$, bearing strength parallel to the grain; $F_{e\perp}$, bearing strength perpendicular to the grain; SD, standard deviation

[a] Evaluated based on the average value of oven-dry specific gravity

[b] From American Society of Civil Engineers[11]

[c] From European Committee for Standardization[10]

[d] From Hirai[8]

[e] Based on six replicates

ferent; no definite maximum load was observed within the embedment range shown by Fig. 3. After crack initiation, indicated by a small load decrease in the load–embedment curve, the applied load increased successively. Bearing load after crack initiation must not be expected for practical use because it will clearly depend on the testing condition. The bearing strength perpendicular to the grain of this study, therefore, was evaluated based on the bearing load at initial cracking. Visual observation of the initial crack was not possible because the susceptible area of the wood was covered by the steel gusset plate. Estimated and experimental bearing strength for loading parallel and perpendicular to the grain are summarized in Table 1.

Bearing strength estimated by empirical equations and obtained from the experiment are presented in Fig. 4. Although these three empirical equations were derived from test results of different wood species, specimen dimensions, and test configurations, their bearing strength parallel to the grain were closer to each other than those for loading perpendicular to the grain. Figure 4a shows that the estimated bearing strength given by NDS was higher than that given by Eurocode 5 or the experimental results. This discrepancy corresponded to the difference of test methods. In the half-hole test method as used in NDS, the bolt was uniformly loaded along its length, producing a uniform stress distribution through the projected bearing area. Meanwhile, in the full-hole test as adopted in Eurocode 5 and this study, the load was applied only at both ends of a bolt, so that uneven application of load at both ends might incline the bolt axis or induce some bending in the bolt. In the full-hole test, therefore, the effective bearing area might be reduced. Average bearing strength as presented in Table 1 differs slightly from the estimation given by Eurocode 5, but deviates substantially from predictions given by NDS or Hirai.[8] This finding was supported by the fact that only Eurocode 5 considered a very wide range of specific gravity in the experiment, including the specific gravity that was close to the specific gravity of wood specimens used in this study. Table 1 indicates that experimental bearing strength was 7.25% lower than the bearing strength of Eurocode 5. For practical use, therefore, some modifications or restrictions are probably required when the empirical equation given by Eurocode 5 is used.

Experimental and estimated bearing strengths for loading perpendicular to the grain are shown in Fig. 4b. Besides

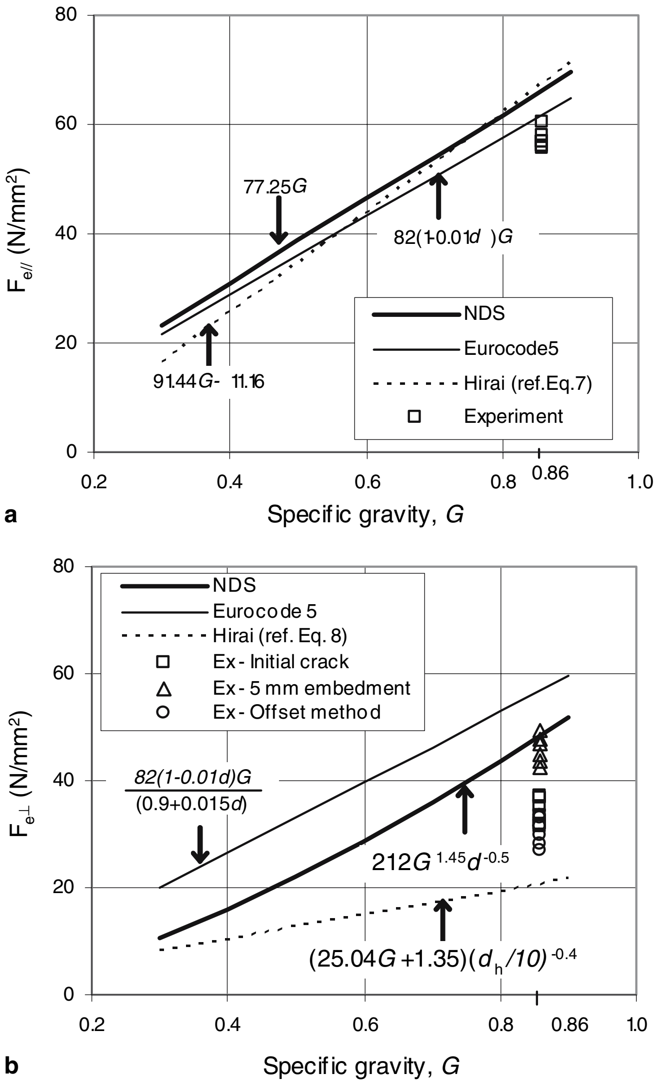

Fig. 4a, b. Comparison of experimental and estimated bearing strength for **a** parallel loading to the grain, and **b** perpendicular loading to the grain

the experimental bearing strength at initial cracking, bearing strength at fastener embedment of 5 mm was evaluated and compared with the bearing strength estimated by Eurocode 5. Bearing strength at fastener embedment of 5 mm has been introduced by Eurocode 5 in the case when a definite maximum bearing load is not observed for fastener embedment of up to 5 mm. The bearing strength at fastener embedment of 5 mm obtained from the test ranged from 42.39 to 49.28 N/mm^2 with an average value of 45.84 N/mm^2. Figure 4b shows that this experimental bearing strength was lower than the bearing strength of Eurocode 5. This difference was probably caused by the smaller wood specimens used in this study. A wood specimen under loading perpendicular to the grain could be assumed as a beam with a concentrated load and being supported along its horizontal margin. As the bolt penetrates the wood specimen, the tensile stress perpendicular to the grain develops along the horizontal margin of the wood specimen with an intensity that depends on the end boundary conditions. The intensity of this stress is very high at the edge of the bolt hole and goes to a minimum at the free end. In the wood specimens of Eurocode 5, the intensity of tensile stress perpendicular to grain at the free end should be small or negligible because the horizontal margin of the wood specimen is long. On the other hand, the intensity of tensile stress at the free end in wood specimens with short horizontal margins used in this study was comparatively higher so that the cracks initiated at the bolt hole propagated more easily to the free end and reduced the maximum bearing load. Fracture analysis has proven that the maximum compressive load increased with increasing horizontal margin of wood specimen.[15]

Test results presented in Fig. 4b indicate that the experimental bearing strength obtained through the 5% offset method was lower than the bearing strength given by NDS, although the horizontal margins of the wood specimens and NDS were similar. The bearing strength evaluated using the 5% offset method varied from 28.01 to 33.66 N/mm^2 with an average value of 30.44 N/mm^2. In the half-hole test configuration as used by NDS, the bolt hole was separated to two half holes before testing so that the crack never initiated at the edge of the bolt hole. Crack initiation directly beneath the bolt as generally observed in the half-hole test method[2] required higher load magnitude than when crack initiation occurred at the edge of the bolt hole. This ensures the bearing load that can be supported by a half-hole specimen is higher than that of a full-hole specimen when the horizontal margins of the specimens are equal. For practical use, bearing strength evaluation of tropical hardwood species based on initial cracking is more appropriate than that based on 5% offset or fastener embedment at 5 mm, because most hardwood species show significant load drop or sudden failure at crack initiation.[16] Because experimental bearing strength perpendicular to the grain at initial cracking could not be properly estimated by any empirical equations of the previous studies or design standards, further investigation seems to be required so that an empirical equation can be proposed.

Hirai's bearing strength for loading perpendicular to the grain,[8] computed by Eq. 8, was the lowest among the results or the evaluations considered here. Hirai's test configuration (see Fig. 1c) was an example of a tension-type bearing test, while the test configurations of Eurocode 5 and NDS were compression-type bearing tests.[9] In the compression-type bearing tests, the wood specimens could bear additional load after crack initiation because propagation of cracks to the ends of the wood specimens were restrained by compressive reaction forces. In wood specimens in the tension-type test, on the other hand, cracks initiated at the vicinities of bolt hole propagated easily to the free ends of the wood specimens. The bearing strength detected by the tension-type tests, therefore, describes the cleavage strength, which is naturally lower than the bearing strength defined by the European yield model. This finding showed that the bearing strength for the loading direction perpendicular to the grain was more sensitive to the difference of specimen dimensions and test configurations than the bearing strength for loading parallel to the grain.

Because a relatively small number of replicates were tested, only definite trends and the average values are discussed. The bearing strength of wood specimens was significantly affected by loading angle to the grain. It decreased as the loading angle to the grain changed from parallel to perpendicular and could be approximated by Hankinson's formula with the property dependence constant m set to 2.0, as shown in Fig. 5. The same value of constant m was also introduced by NDS to evaluate the bearing strength for intermediate loading angle to the grain. The empirical equation proposed by Ehlbeck and Werner[5] (Eq. 3) seemed to be less sensitive for different loading angles to the grain.

A typical bearing stress–embedment curve obtained from this experiment was approximated by a linear elastic–plastic diagram confirming the assumption of yield theory. Besides the ultimate bearing stress, some important bearing stress points such as the proportional limit, the 5% offset, and the yield stress were investigated to provide a sufficient description of the experimental bearing stress–embedment curve. These stress points are defined according to Fig. 6. The stress ratio with respect to the ultimate bearing stress of these points was high when the angles of loading to the grain were 0°, 30°, and 45°, and it was small for other loading angles to the grain. The dispersion of this stress ratio

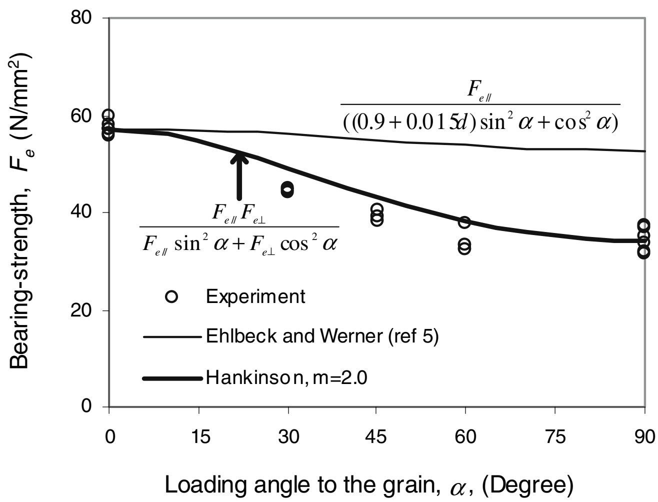

Fig. 5. Effect of loading angle to the grain on bearing strength

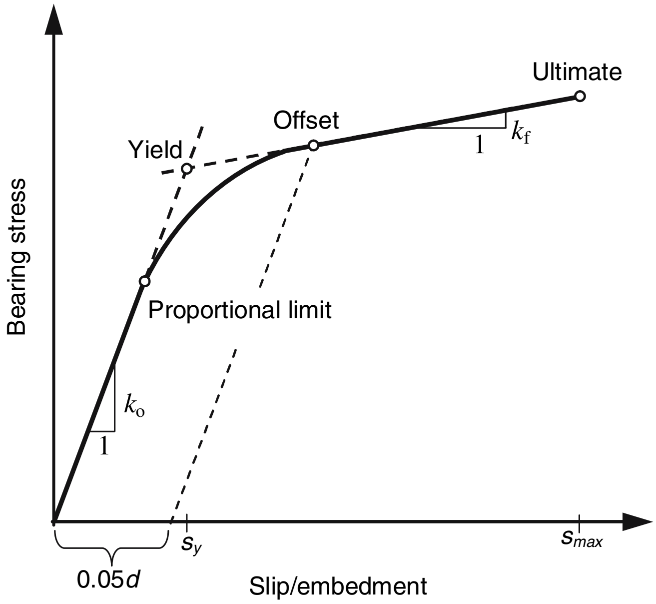

Fig. 6. Typical bearing stress–embedment curve and parameter definitions. k_o, Initial stiffness; k_f, final stiffness

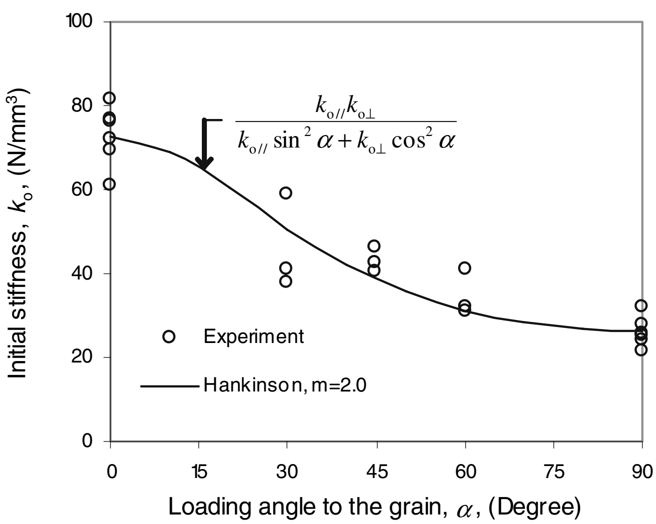

Fig. 7. Effect of loading angle to the grain on the initial stiffness (k_o)

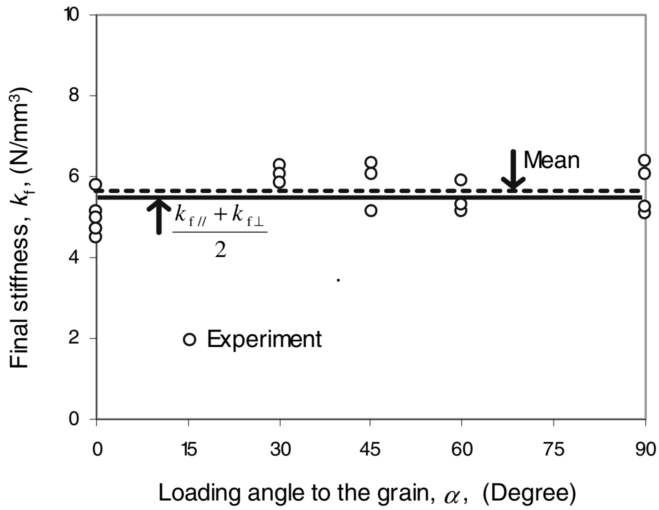

Fig. 8. Effect of loading angle to the grain on the final stiffness (k_f)

Table 2. Stiffness of bearing stress–embedment curve

α (degrees)	k_o (N/mm^3)	k_f (N/mm^3)	k_f / k_o
0[a]	72.8 ± 7.1	5.0 ± 0.5	0.07
	(60.9–81.4)	(4.5–5.8)	(0.06–0.07)
30[b]	46.0 ± 11.5	6.1 ± 0.2	0.14
	(38.0–59.2)	(5.9–6.3)	(0.11–0.16)
45[b]	43.0 ± 2.9	5.8 ± 0.6	0.14
	(40.4–46.1)	(5.1–6.3)	(0.11–0.16)
60[b]	34.6 ± 5.5	5.4 ± 0.4	0.16
	(31.0–42.6)	(5.1–5.9)	(0.13–0.19)
90[a]	26.2 ± 3.4	5.7 ± 0.5	0.22
	(21.8–31.9)	(5.1–6.4)	(0.19–0.27)

α, Loading angle to the grain; k_o, initial stiffness; k_f, final stiffness
Data given as mean standard deviation with range shown in parentheses
[a] Based on six replicates
[b] Based on three replicates

was about 10%–20%. The average bearing stresses at the 5% offset point, yield point, and at the proportional limit were found to be 0.87, 0.75, and 0.59 times the ultimate bearing strength, respectively.

The initial stiffness[17] of the bearing stress–embedment curve (k_o) was also an important mechanical property besides bearing strength because many researchers have identified it with other names: bearing constant[18] or foundation modulus.[19,20] This mechanical property, in particular, is required for load–slip relationship analysis of bolted joints using beam on elastic foundation theory. A similar situation to that of bearing strength was observed; the experimental bearing stress–embedment curves indicated that the initial stiffness decreased as the loading angle changed from parallel to perpendicular to the grain (see Fig. 7). Curve fitting using Hankinson's formula gave the least-square error when the value of m was equal to 2.0. In contrast to the initial stiffness, the final stiffness (k_f) of the bearing stress–embedment curve seemed to be negatively affected by the loading angle to the grain. Besides the initial stiffness, the final stiffness of the bearing stress–embedment curve is also required for inelastic design of dowel-type joints. From the test results, it was found that the mean final stiffness of any loading angle to the grain can be conservatively replaced by the average value between the values of final stiffness for loading parallel and perpendicular to the grain, as shown in Fig. 8.

Table 2 shows that the ratio of the final stiffness to initial stiffness was the highest when loading angle was perpendicular to the grain. On the other hand, this ratio was very low for loading angles parallel to the grain. The higher final stiffness arose from the fact that wood fibers compressed and bent as layered beams beneath the bolt were still capable of carrying additional load even after initial splitting had taken place. This condition is well observed when the wood member is loaded perpendicular to the grain in compression-type bearing configurations.[9] In the case of loading

Table 3. Fastener embedment (s)

α (degrees)	s_y (mm)	s_{max} (mm)	s_{max} / s_y
0[a]	0.52 ± 0.55 (0.47–0.57)	2.74 ± 0.63 (2.12–3.37)	5.40 (3.72–7.17)
30[b]	0.77 ± 0.18 (0.56–0.88)	2.28 ± 0.22 (2.03–2.44)	3.03 (2.70–3.63)
45[b]	0.70 ± 0.03 (0.67–0.74)	2.46 ± 0.07 (2.39–2.53)	3.59 (3.23–3.66)
60[b]	0.67 ± 0.16 (0.49–0.81)	2.91 ± 0.14 (2.74–2.99)	4.59 (3.38–6.10)
90[a]	0.97 ± 0.01 (0.96–0.97)	2.72 ± 0.33 (2.39–3.05)	2.82 (2.49–3.14)

s_y, Fastener embedment at yield point; s_{max}, fastener embedment at maximum load
Data given as mean standard deviation with range shown in parentheses
[a] Based on six replicates
[b] Based on three replicate

parallel to the grain, buckling of wood fibers beneath the bolt results in lower strain-hardening rate. Fastener embedment presented in Table 3 shows the wood specimen loaded parallel to the grain had higher s_{max} / s_y (ratio between embedment at maximum and "yield" bearing stress) than the other specimens. For the case of loading parallel to the grain, cracks propagated in a stable fashion up to final rupture, resulting in higher fastener embedment beyond the yield point. More specimens are required to support this finding.

Conclusions

A study on the bearing properties of *Shorea obtusa* under a double-shear test configuration is reported. The average bearing strengths parallel and perpendicular to the grain were found to be 57.30 and 34.37 N/mm^2, respectively. Experimental bearing strength parallel to the grain was 7.25% lower than estimation given by Eurocode 5. Bearing strength perpendicular to the grain at initial cracking could not be properly estimated by any of the empirical equations of previous studies or design standards. Therefore, further investigation seems to be required so that an empirical equation can be proposed. The ultimate bearing strength and initial stiffness decreased as the loading angle changed from parallel to perpendicular to the grain and could be approximated by Hankinson's formula with the property dependence constant (m) set to 2.0. The final stiffness seemed to be unaffected by the angle of loading to the grain and its mean value for any loading angle to the grain could be replaced by the average value between the values of final stiffness for loading parallel and perpendicular to grain.

Acknowledgments The work presented in this article was conducted at the Material Testing Laboratory of the Civil Engineering Department, Chulalongkorn University. The first author (A.A.) thanks the Japan International Cooperation Agency (JICA) through the AUN/SEED-Net program for the educational scholarship and the research funding provided to this project. The comments and suggestions of Prof. Dr. Ekasit Limsuwan and Dr. Anat Ruangrassamee of Chulalongkorn University are much appreciated.

References

1. Faherty KF, Williamson TG (1999) Wood engineering and construction. McGraw-Hill, New York
2. Rammer DR (2001) Effect of moisture content on nail bearing strength. Research Paper FPL-RP-591. Forest Products Laboratory, Forest Service, US Department of Agriculture, Madison, WI
3. Johansen KW (1949) Theory of timber connections. Int Assoc Bridge Struct Eng 9:249–262
4. Whale LRS, Smith I (1986) The derivation of design values for nailed and bolted joints in EUROCODE 5. Working Commission 18, Timber Structures, Meeting 19, International Council for Building Research Studies and Documentation
5. Ehlbeck J, Werner H (1992) Softwood and hardwood embedding strength for dowel type fasteners. Working Commission 18, Timber Structures, Meeting 25, International Council for Building Research Studies and Documentation
6. Soltis AL, Wilkinson TL (1991) United States adaptation of European yield model to large diameter dowel fastener specification. Proc Int Timber Eng Conf 3:43–49
7. Wilkinson TL (1991) Dowel bearing strength. Research Paper FPL-RP-505, Forest Products Laboratory, Forest Service, US Department of Agriculture, Madison, WI
8. Hirai T (1989) Basic properties of mechanical wood-joints II: bearing properties of wood under a bolt. Res Bull Coll Exp Forest Fac Agric Hokkaido Univ 46:967–988
9. Hirai T (1989) Rational testing methods for determination of basic lateral resistance of bolted wood-joints. Res Bull Coll Exp Forest Fac Agric Hokkaido Univ 46:959–966
10. European Committee for Standardization (1995) Eurocode 5. Design of timber structures European pre-standard ENV 1995-1-1: general rules and rules for building. CEN, European Committee for Standardization, Brussels
11. American Society of Civil Engineers (1997) National design and specification for timber construction of US. American Society of Civil Engineers, New York
12. Soerianegara I, Lemmens RHMJ (eds) (1993) Timber trees: major commercial timbers. Plant resources of South-East Asia, vol. 5. Pudoc Scientific, Wageningen, p 432
13. Hirai T, Sawada M (1982) Some considerations on nail-wood bearing test. Mokuzai Gakkaishi 28:39–44
14. Harada M, Hayashi T, Karube M, Komatsu K (2000) Dowel-bearing properties of glue laminated timber with a drift pin. Proceedings of World Conference on Timber Engineering, July 2000, British Columbia
15. Yasumura M, Daudeville L (1996) Fracture analysis of bolted timber joints under lateral force perpendicular to the grain. Mokuzai Gakkaishi 42:225–233
16. Reiterer A, Sinn G, Stanzl-Tschegg SE (2002) Fracture characteristics of different wood species under mode I loading perpendicular to the grain. J Mater Sci Eng A332:29–36
17. Gattesco N (1998) Strength and local deformability of wood beneath bolted connectors. J Struct Eng 124:195–202
18. Hirai T (1985) Nonlinear load–slip relationship of bolted wood-joints with steel side-members III. Advanced numerical analysis based on the generalized theory of beam on an elastic foundation. Mokuzai Gakkaishi 31:165–170
19. Foschi RO (1974) Load–slip characteristics of nails. J Wood Sci 7:69–74
20. Jensen JL (2005) Quasi-non-linear fracture analysis of the double cantilever beam specimen. J Wood Sci 51:566–571