Title page

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

Shorea obtusa のボルト面圧性能

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Key words:

Bearing strength・Initial stiffness・Loading angle to the grain・*Shorea obtusa*

Abstract

Empirical equations to determine the bearing strength have been proposed by many researchers and design standards. Since those 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 those 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. Test showed the average bearing strength parallel to the grain was 7.25% lower than prediction given in Eurocode 5. The bearing strength perpendicular to the grain evaluated based on bearing load at initial crack was different largely from any predictions given by previous studies or design standards. It was also found that the bearing strength and initial stiffness of bearing stress-embedment curve for loading at intermediate angle to the grain could be satisfactorily predicted with Hankinson's formula.

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

Introduction

Tropical hardwood species are, in most ASEAN countries, usually used for many types of structures such as residential houses, historical buildings, bridges, etc. 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 be visually observed as in softwood species. When the strength of tropical timber connection is analyzed by using the yield theory,[3] the bearing strength of 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 since those equations were developed mainly based on test data of softwood species. This study is aimed to investigate the bearing properties of *Shorea obtusa***,** which is one of most popular tropical hardwood species in ASEAN countries, and to examine whether the equations proposed by previous researchers and standards well predict the test results or not. Finally, findings in this study will ease the use of yield theory and utilize the tropical hardwood species more efficiently.

Literature review

Previous works regarding the bearing strength of wood concluded the diameter of fasteners, the 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, since the bearing resistance is very sensitive to specimen dimensions and test configurations, trials to validate those equations are consequently required. Two types of test methods commonly used to evaluate the bearing strength are 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. 1(a). They proposed Eq. 1 and Eq. 2 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 mm, while the oven-dry specific of wood (G) is unitless.

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

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

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 hard wood species. (Species name and its average specific gravity: *Picea abies*, 0.422; *Fagus sylvatica*, 0.714; *Quercus robur* and *Quercus petraea*, 0.733; *Tectona grandis*, 0.652; *Intsia*, 0.804; *Afzelia*, 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} equaled to $1.35+0.015d$ for softwood species and equaled to $0.9+0.015d$ for hardwood species.

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

The half-hole test as shown in Fig. 1(b) was proposed by Soltis and Wilkinson,[6] Wilkinson,[7] and it was adopted by 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), they suggested Eq. 4 and Eq. 5 to estimate the bearing strength for loading angle 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.

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

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

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

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 bolt-hole expressed in mm. Hirai's empirical equations were based on test data of some wood species (Spruce, Hemlock, and Douglas fir) with specific gravity varied from 0.38 to 0.55 under the test configuration shown in Fig. 1(c).

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

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

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

Materials and methods

Wood of *Shorea obtusa* and bolts of diameter 12.4 mm were used in this study. This wood has been commercially known with some popular names: Balau or Taeng among ASEAN countries. The specific gravity of this wood at 15% of 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 system. Wood specimens were purchased at one local lumber retailer and were kept inside the testing laboratory for a couple of weeks before tested. No specific seasoning process was applied to adjust the moisture content of the wood specimens.

Double-shear bearing test shown in Fig. 1(d) 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 wood was continuously measured by using two linear variable differential transducers (LVDTs). The bearing displacement measurement shown in Fig. 1(d) 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, 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 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 thickness. Since 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 matched samples technique as shown in Fig. 2. The dimension of wood specimen of this study was prepared to be smaller than that of the Eurocode 5 as shown in Fig. 1(d) because of size restriction of wood piece that we purchased. 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 discussions

From twenty one wood specimens, it was found that the moisture content of the specimens varied from 12.35% to 17.51% and having 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 different; 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 since it will clearly depend on testing condition. The bearing strength perpendicular to the grain of this study, therefore, was evaluated based on the bearing load at initial crack. Visual observation of initial crack was not successfully performed since the potential crack of wood, initiated beneath the bolt, 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 is 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. Fig. 4(a) shows that the estimated bearing strength given by NDS was higher than that of Eurocode 5 or experimental results. This discrepancy was 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 and 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 largely from predictions given by NDS or Hirai. 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 close to the specific gravity of wood specimen used in this study. Table 1 indicates that experimental bearing strength was 7.25% lower than bearing strength of Eurocode 5. For practical use, therefore, some modifications or restrictions are surely required when the empirical equation given by Eurocode 5 will be used.

Experimental and estimated bearing strength for loading perpendicular to the grain is shown in Fig. 4(b). Besides the experimental bearing strength at initial crack, bearing strength at 5 mm fastener embedment was evaluated and compared with the bearing strength estimated by Eurocode 5. Bearing strength at 5 mm fastener embedment has been introduced by Eurocode 5 in the case when a definite maximum bearing load within 5 mm fastener embedment is not observed. The bearing strength at 5 mm fastener embedment obtained from the test ranged from 42.39 N/mm^2 to 49.28 N/mm^2 with an average value of 45.84 N/mm^2. Fig. 4(b) shows that this experimental bearing strength was lower than the bearing strength of Eurocode 5. This result was potentially caused by smaller wood specimens used in this study. 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 into the wood specimen, the tensile stress perpendicular to the grain is developed along the horizontal margin of wood specimen with different intensity depending on the end boundary conditions. The intensity of this stress is very high at the edge of the bolt-hole and goes to minimum at the free end. In wood specimen of Eurocode 5, the intensity of tensile stress perpendicular to grain at free end should be small or negligible because the horizontal margin of wood specimen was long. The intensity of tensile stress at free end in wood specimen with short horizontal margin used in this study, on the other hand, was comparatively higher so that the cracks initiated at the bolt-hole propagated more easily to the free end and reducing 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. 4(b) indicates that the experimental bearing strength obtained through 5-percent offset method was lower than the bearing strength given by NDS, though the horizontal margin of wood specimen and NDS was almost similar. The bearing strength evaluated using 5-percent offset method varied from 28.01 N/mm^2 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 bolt-hole. The crack initiation at directly beneath the bolt as generally observed in half-hole test method[2] required higher load magnitude than that when crack initiation occurs at edge of bolt-hole. This ensures the bearing load can be supported by a half hole specimen is higher than that of a full-hole specimen when the horizontal margin of those specimens is equal. For practical use, bearing strength evaluation of tropical hardwood species based on initial crack is more appropriate than based on 5-percent offset or 5 mm fastener embedment because most hardwood species always show significant load drop or sudden failure when crack initiated.[16] Since experimental bearing strength perpendicular to the grain at initial crack could not 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, computed by Eq. (8), was the lowest among the results or the evaluations considered here. Hirai's test configuration (see Fig. 1(c)) was an example of tension-type bearing test, while the test configuration of Eurocode 5 and NDS were compression-type bearing test.[9] In compression-type bearing test, wood specimen can bear additional loads after crack initiations because propagations of them to the end of wood specimens were restrained by compressive reaction forces. In wood specimen of tension-type test, on the other hand, cracks initiated at the vicinities of bolt-hole propagated easily to the free ends of wood specimens. The bearing strength detected by the tension-type tests, therefore, describes the cleavage strength, which is naturally lower than bearing strength defined by the European yield model. This finding showed that the bearing strength for loading direction perpendicular to the grain was more sensitive to the difference of specimen dimensions and test configurations than the bearing strength for parallel to the grain.

Since the relatively small number of replicates was tested, only definite trend and the average value were discussed. 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 equals 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. Empirical equation proposed by Ehlbeck and Werner (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-percent 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. 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 was about 10 to 20 percent. The average bearing stress at 5-percent offset point, yield point, and at proportional limit were found as 0.87, 0.75, and 0.59 times of the ultimate bearing strength, respectively.

The initial stiffness[17] of bearing stress-embedment curve (k_o) was also an important mechanical property besides bearing strength as many researchers identified it with some 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 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 bearing stress-embedment curve seemed to be negatively affected by the loading angle to the grain. Besides the initial stiffness, the final stiffness of bearing stress-embedment curve is also required for inelastic design of dowel-type joint. 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 final stiffness of loading parallel and perpendicular to grain as shown in Fig. 8.

Table 2 shows the ratio of the final stiffness to the initial stiffness was the highest when loading angle is perpendicular to the grain. On the other hand, this ratio was very low for loading angle parallels to the grain. The higher final stiffness arises from the fact that wood fibers compressed and bent as layered beams beneath the bolt are still capable to carry more additional load even after initial splitting is 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 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 higher fastener embedment beyond the yield point. Yet, more specimens are required to support this finding.

Conclusions

A study on bearing properties of *Shorea obtusa* under a double-shear test configuration was reported in this paper. The average bearing strength parallel and perpendicular to the grain was found as 57.30 N/mm^2 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 crack could not properly estimated by any empirical equations of the 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) equals 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 final stiffness of loading parallel and perpendicular to grain.

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Table Captions

Table 1. Estimated and experimental bearing strength

$F_{e//}$: Bearing strength parallel to the grain

$F_{e\perp}$: Bearing strength perpendicular to the grain

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

[b] Based on six replicates

Avg: average value; Min: minimum value; Max: maximum value; STD: standard deviation

Table 2. Stiffness of bearing stress-embedment curve

k_o : Initial stiffness

k_f : Final stiffness

[a] Based on six replicates

[b] Based on three replicates

[1] Average value

[2] Values in parentheses are minimum and maximum values

[3] Standard deviation

Table 3. Fastener embedment (s)

s_y : Fastener embedment at "yield" point

$s_{\max}$: Fastener embedment at maximum load

[a] Based on six replicates

[b] Based on three replicates

[1] Average value

[2] Values in parentheses are minimum and maximum values

[3] Standard deviation

Table 1

	NDS[a] (Eq. 4 or 5)	Eurocode 5[a] (Eq. 1 or 2)	Hirai[a] (Eq. 7 or 8)	Experiment[b] Avg	Min - Max	STD
$F_{e//}$ (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

Table 2

	Loading angle to the grain, α , (deg)				
	0 [a]	30 [b]	45 [b]	60[b]	90[a]
k_o (N/mm^3)	72.8[1]	46.0	43.0	34.6	26.2
	(60.9 - 81.4)[2]	(38.0 – 59.2)	(40.4 – 46.1)	(31.0 – 42.6)	(21.8 – 31.9)
	7.1[3]	11.5	2.9	5.5	3.4
k_f (N/mm^3)	5.0	6.1	5.8	5.4	5.7
	(4.5 – 5.8)	(5.9 – 6.3)	(5.1 – 6.3)	(5.1 – 5.9)	(5.1 – 6.4)
	0.5	0.2	0.6	0.4	0.5
k_f / k_o	0.07	0.14	0.14	0.16	0.22
	(0.06 – 0.07)	(0.11 – 0.16)	(0.11 – 0.16)	(0.13 – 0.19)	(0.19 – 0.27)

Table 3

	Loading angle to the grain, α, (deg)				
	0[a]	30[b]	45[b]	60[b]	90[a]
s_y (mm)	0.52[1]	0.77	0.70	0.67	0.97
	(0.47 – 0.57)[2]	(0.56 – 0.88)	(0.67 – 0.74)	(0.49 – 0.81)	(0.96 – 0.97)
	0.55[3]	0.18	0.03	0.16	0.01
s_{max} (mm)	2.74	2.28	2.46	2.91	2.72
	(2.12 – 3.37)	(2.03 – 2.44)	(2.39 – 2.53)	(2.74 – 2.99)	(2.39 – 3.05)
	0.63	0.22	0.07	0.14	0.33
s_{max} / s_y	5.40	3.03	3.59	4.59	2.82
	(3.72 – 7.17)	(2.70 – 3.63)	(3.23 – 3.66)	(3.38 – 6.10)	(2.49 – 3.14)

Figure Captions

Fig. 1. Several bearing test configurations (measurement in mm)

(a) Test configuration of Eurocode 5; (b) Half-hole test of National Design and Specification (NDS); (c) Hirai's test configuration (ref. 8); And (d) Full-hole test adopted in this study

d : Bolt diameter

α : Loading angle to the grain

LVDT : Linear variable differential transducer

⇀ : Grain orientation

Fig. 2. Wood specimen fabrication

d : Bolt diameter

α : Loading angle to the grain

⇀ : Grain orientation

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

Fig. 4. Comparison of experimental and estimated bearing strength

(a) Parallel loading to the grain; And (b) Perpendicular loading to the grain

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

Fig. 6. Typical bearing stress-embedment curve and parameter definitions

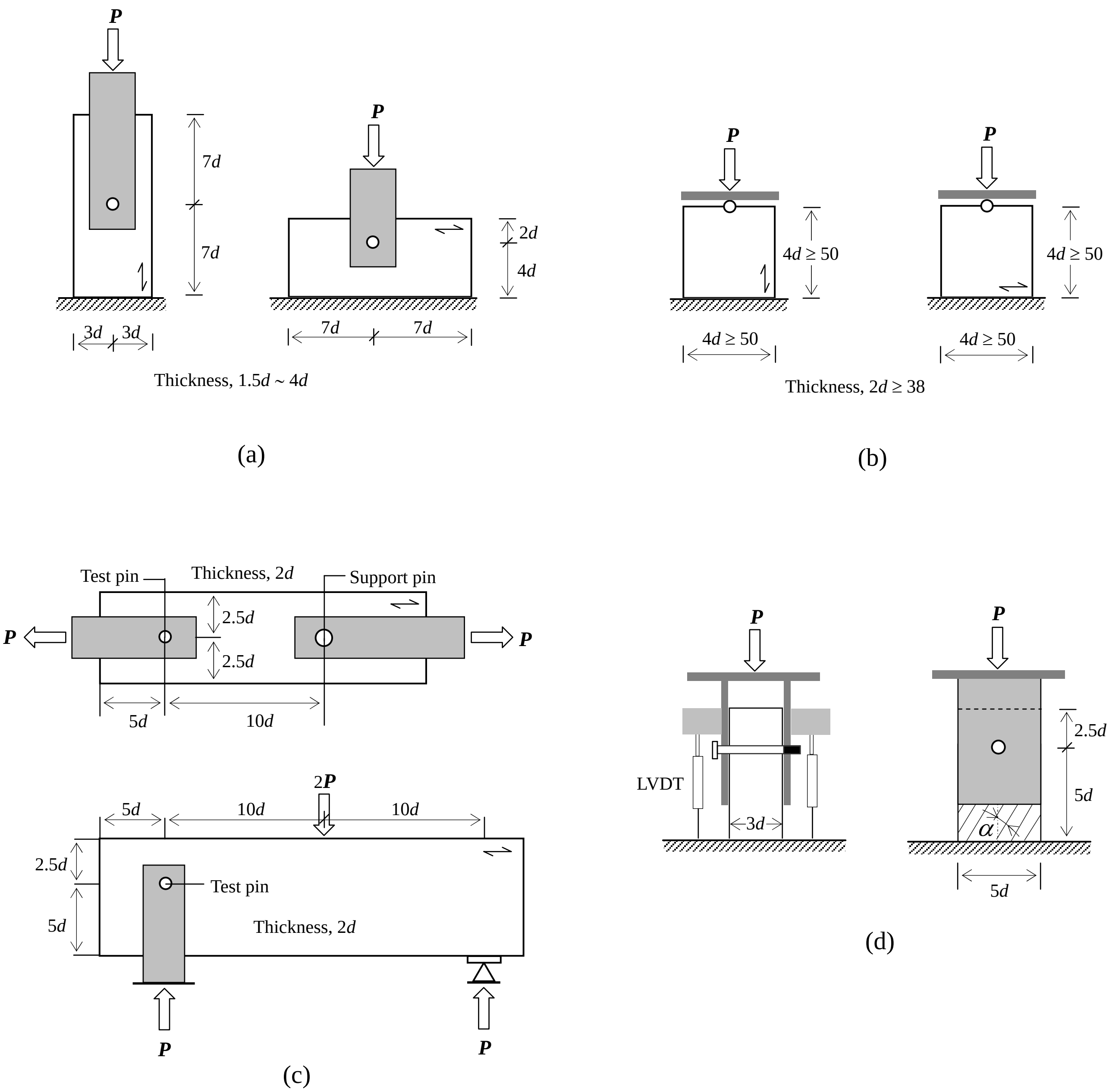
d : Bolt diameter

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)


P
7d
7d
3d
3d
P
2d
4d
7d
7d
Thickness, 1.5d ~ 4d
(a)
P
P
4d ≥ 50
4d ≥ 50
4d ≥ 50
4d ≥ 50
Thickness, 2d ≥ 38
(b)
Test pin
Thickness, 2d
Support pin
P
P
2.5d
2.5d
5d
10d
2P
5d
10d
10d
2.5d
5d
Test pin
Thickness, 2d
P
P
(c)
P
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LVDT
3d
2.5d
5d
α
5d
(d)

Fig. 1

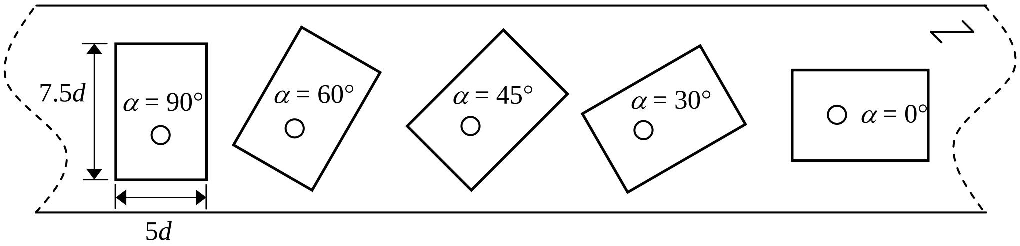
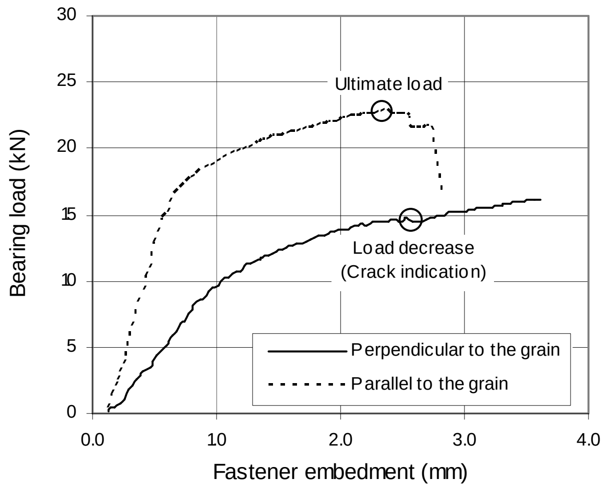


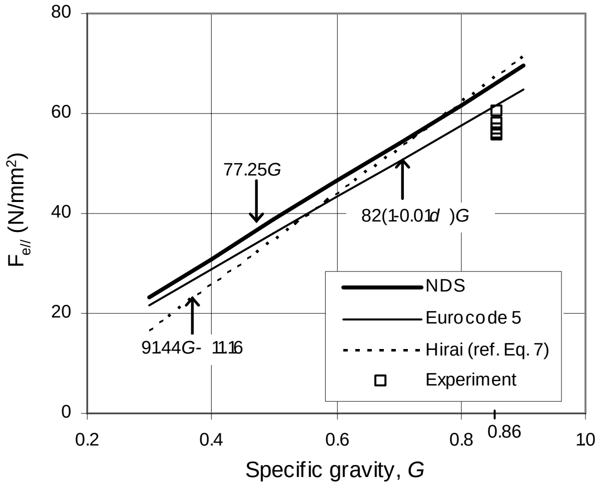
Fig. 2



30
25
20
15
10
5
0
Bearing load (kN)
0.0
10
2.0
3.0
4.0
Fastener embedment (mm)
Ultimate load
Load decrease
(Crack indication)
Perpendicular to the grain
Parallel to the grain

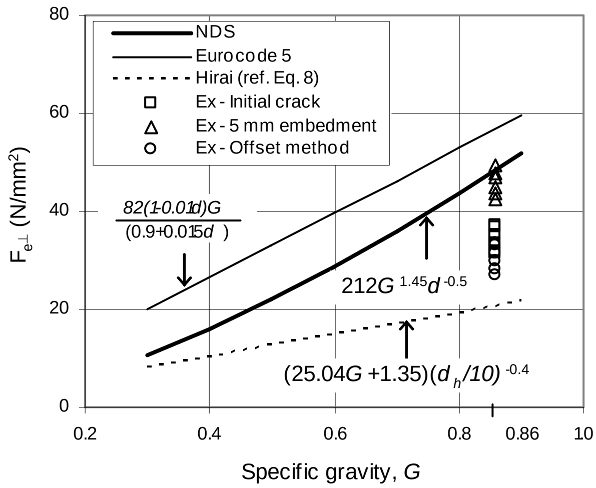
Fig. 3

(a)



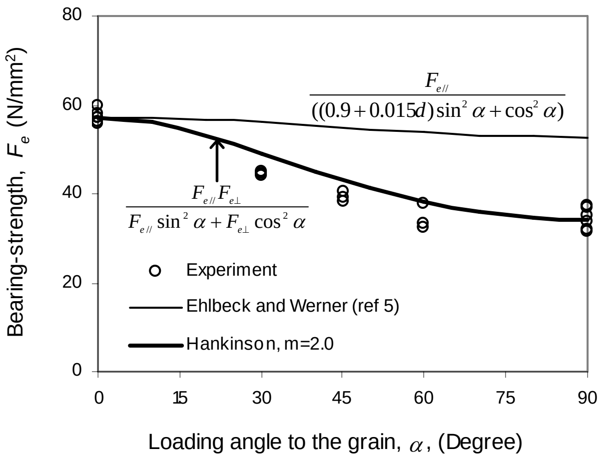
80
60
40
20
0
0.2
0.4
0.6
0.8
0.86
10
$F_{e//}$ (N/mm²)
Specific gravity, G
77.25G
82(1-0.01d)G
9144G- 116
NDS
Eurocode 5
Hirai (ref. Eq. 7)
Experiment

(b)



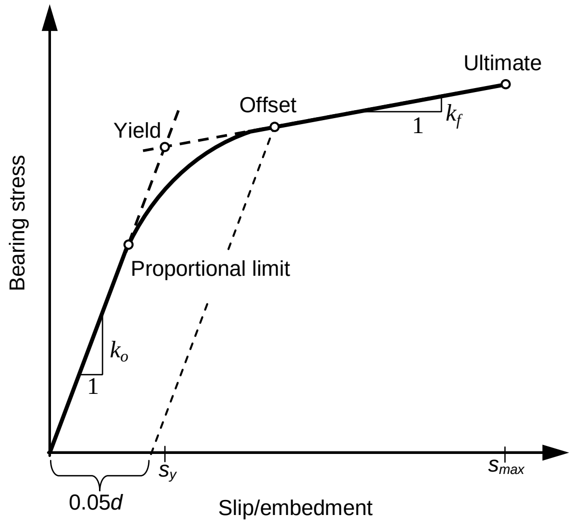
80
60
40
20
0
0.2
0.4
0.6
0.8
0.86
10
$F_{e\perp}$ (N/mm²)
Specific gravity, G
NDS
Eurocode 5
Hirai (ref. Eq. 8)
Ex - Initial crack
Ex - 5 mm embedment
Ex - Offset method
82(1-0.01d)G / (0.9+0.015d)
212G 1.45d -0.5
(25.04G +1.35)(d h/10) -0.4

Fig. 4



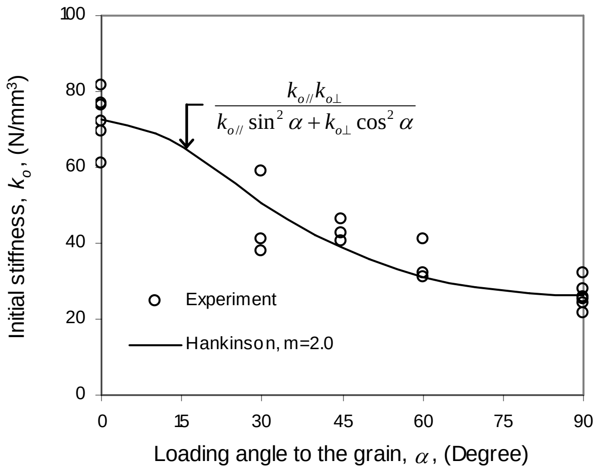
80
60
40
20
0
Bearing-strength, F_e (N/mm^2)
$\frac{F_{e//}}{((0.9+0.015d)\sin^2\alpha+\cos^2\alpha)}$
$\frac{F_{e//}F_{e\perp}}{F_{e//}\sin^2\alpha+F_{e\perp}\cos^2\alpha}$
Experiment
Ehlbeck and Werner (ref 5)
Hankinson, m=2.0
0
15
30
45
60
75
90
Loading angle to the grain, α, (Degree)

Fig. 5



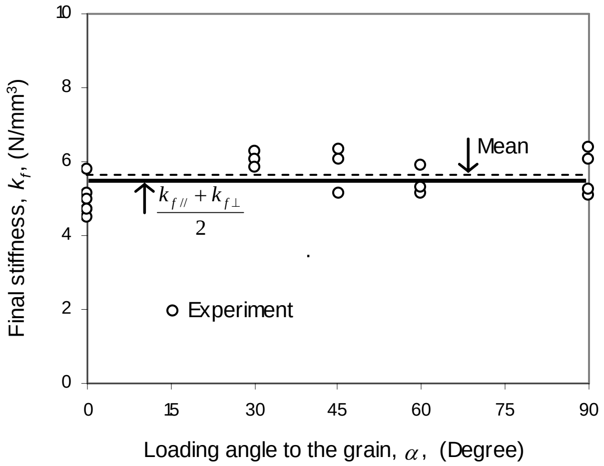
Ultimate
Offset
Yield
k_f
1
Bearing stress
Proportional limit
k_o
1
s_y
s_{max}
0.05d
Slip/embedment

Fig. 6



100
80
60
40
20
0
0
15
30
45
60
75
90
Initial stiffness, k_o, (N/mm^3)
Loading angle to the grain, α, (Degree)
$\frac{k_{o//}k_{o\perp}}{k_{o//}\sin^2\alpha + k_{o\perp}\cos^2\alpha}$
Experiment
Hankinson, m=2.0

Fig. 7



Final stiffness, k_f, (N/mm³)
10
8
6
4
2
0
0
15
30
45
60
75
90
Loading angle to the grain, α, (Degree)
Mean
$\frac{k_{f//} + k_{f\perp}}{2}$
Experiment

Fig. 8