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NOTE

Evaluation of embedding strength on Uruguayan wood to apply the European yield theory for double shear bolted joint

Alejandro Benitez Garcia · Naoyuki Itagaki

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Abstract The main objective of this study was to evaluate embedding strength on Uruguayan wood to apply the European yield theory (EYT) for double shear bolted joints' on *Eucalyptus grandis* H.(EGH). To introduce the dowel-type connection performance, double shear tests were conducted. The embedding tests were conducted to calculate the yield strength of bolted joint by EYT and the compression test, to estimate the embedding strength. The yield strength obtained from the experiments showed a good agreement with the yield strength calculated by EYT method. The yield strength of double shear bolted joint evaluated from compressive strengths is a very close to the yield strength calculated by EYT. The average value and variability of the yield strength of double shear bolted joint calculated by EYT applying the embedding strengths of experimental results were very close to the yield strength or 5 % offset method of experimental results. The results from this study showed a good behavior to structural design with EGH in accordance to the Japanese standard code.

Keywords *Eucalyptus grandis* H. · Yield strength · Embedding strength 5 % offset method · Bolted timber joint

Introduction

The *Eucalyptus grandis* H. (EGH), mainly cultivated in the north region of Uruguay (Rivera), is one of the most important renewable species planted at this moment and can be supplied in large quantities for house building.

To expand the domestic wood demand in Uruguay, a prototype of timber house [1–3] was developed and announced at the World Conference on Timber Engineering (WCTE) 2010 [2]. This timber house structure with Uruguayan EGH was designed in accordance with the Japanese architecture standard [4] based on allowable stress values, which were calculated with experimental data, from tests conducted by Technological Laboratories of Uruguay (LATU [5]) and Japanese International Cooperation Agency (JICA). The collapses seen in wooden structures are caused by failure connections against earthquake or wind force. In addition, calculation based on the prototype of WCTE 2010 showed that large pull-out force occurs in column base joints when the house experiences a horizontal force, resulting from the impact of an earthquake or wind. On timber structures, the hold down connector [6] with bolted joints is generally used for a column base joint. Since there are few examples of joint experiments using EGH [7], it is necessary to verify the shear capacity of the bolted joint and, whether the calculation of its yield strength based on the European yield theory [8] (EYT) is applicable or not.

The Japanese standard was developed by the application of the EYT to calculate the yield strength of bolted joint, based on the embedding strength of wood. In this theory, the embedding strength of wood and the yield moment of the dowel are the governing properties to determine the yield strength of bolted joints. Until now, there are few publications [7] on the importance of the dowel-type connections related to the embedding strength of these lumber species (EGH).

For this reason, it was unclear which value should be used in the Uruguayan EGH because the density and the strength values related to the Japanese standard do not follow the criteria observed for EGH strength values. In

A. Benitez Garcia (✉) · N. Itagaki
Architecture and Environment System, Faculty of Systems Science and Technology, Akita Prefectural University, Tsuchiya 84-4, Yurihonjo, Akita 015-0055, Japan
e-mail: patulab@gmail.com; d10s005@akita-pu.ac.jp

addition, it was not clear whether the correlation between density and embedding strength for EGH could be applied.

The main objective of this study was to prove the applicability of EYT on EGH for double shear bolted joints' (DSB) use and to introduce of the dowel-type connection performance on this timber; double shear tests were conducted applying the embedding strength formulae by Eurocode 5. The embedding tests were conducted to calculate the yield strength of bolted joint by EYT and the compression test, to estimate the embedding strength based on Sawata and Yasumura [9].

To evaluate the applicability of these standards, an embedding strength by the 5 % offset method [10, 11] was examined for a 5-mm embedment [12]. This study proves the applicability of the Japanese standard criteria.

The embedding strength evaluation methods follow the formulae prescribed in European code EN 383 [12] and procedure of 5 % offset method described in ASTM D 5764 [10] and Japanese standard code [11]. In structural design, the embedding capacity is estimated indirectly. Eurocode 5 (EC5) provides equations for estimating the embedding strength as a function of density (EN 1995-1-1:2005) [13].

Materials and methods

In Uruguay, glued laminated timber with a cross section of 120 × 120 mm is often used as columns for house construction. Therefore, it is used as glued laminate timber for a column in the prototype of timber house. In testing of double shear bolted joint glued laminated timber was used.

The modulus of elasticity of the Uruguayan glued laminated timber for five ply specimens (120 × 20 × 600 mm) was measured recording same grade of 12.7×10^3 N/mm^2. The DSB and embedding tests were carried out with the same sample of glued laminated timber (Fig. 1). A portion of the lamina, for which the bolt received a bearing in the DSB test, was cut out for compression parallel to the grain test specimens (3 per each). However, another 42 clear specimens of 20 × 20 × 40 mm (radial, tangential and longitudinal axis, respectively) were cut out for compression test parallel to the grain.

All specimens were conditioned in a controlled climate chamber at 20 ± 2 °C and 65 ± 5 % of relative humidity (RH), in accordance with ASTM D 4442 [14]. Physical properties like, density (ρ) and moisture content (MC), were determined in accordance with test methods by ASTM D 2395 [15]. An universal testing machine (Shimadzu UH 300 kN load machine), capable for applying loads with adequate rate movement of the loading head and accuracy of 1 % of the load, was used for all monotonic tests.

The DSB tests were conducted according ASTM D5652 [16] on six glued laminated timbers with the tension loading parallel to the grain. Test configuration is shown Fig. 2. The bolt was located at the center of the width with a distance of 84 mm (7d) to the end. The 12-mm bolts were

Fig. 1 Cut out specimens from glued laminated timber of EGH

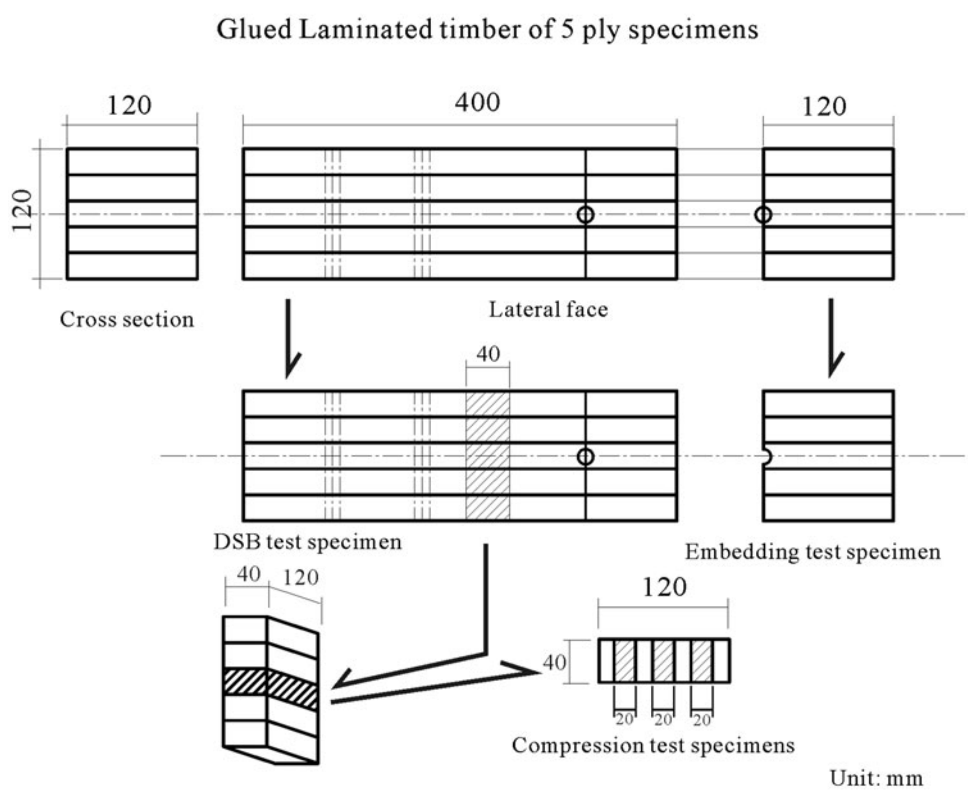
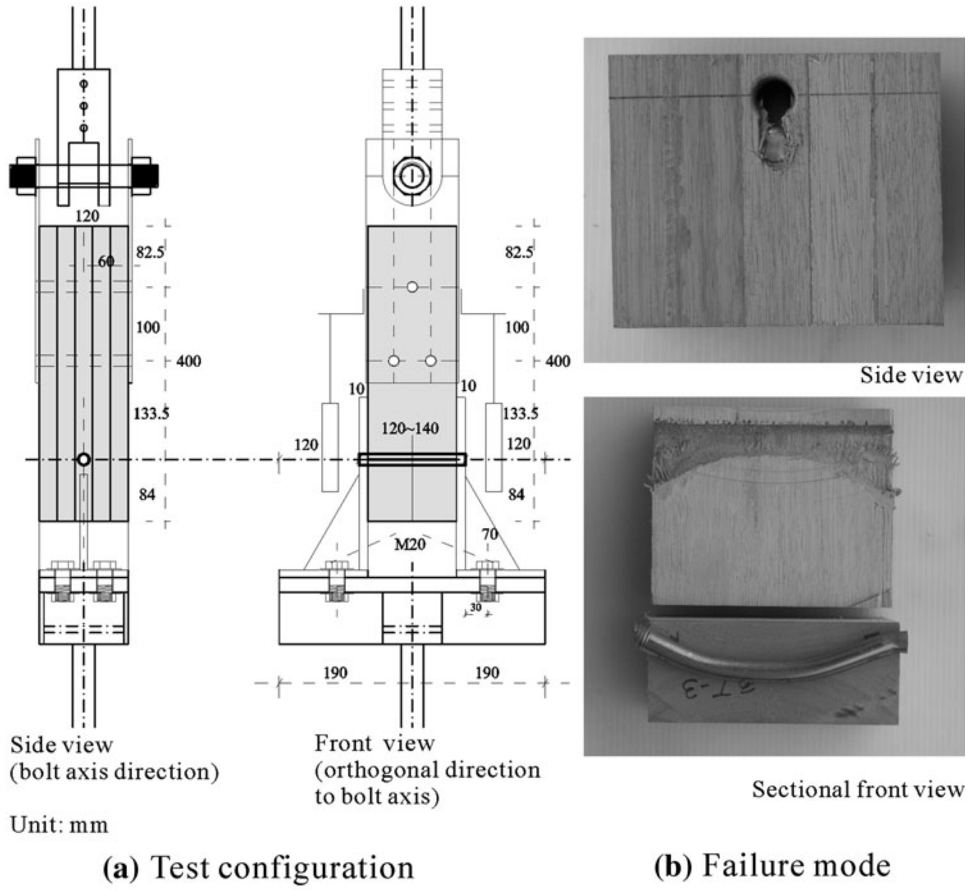


Fig. 2 Double shear bolted joint **a** test configuration, **b** failure mode of bolted joint



arranged parallel to the adhesive interface of the lamina, where the thickness (l) and bolt diameter (d) ratio l/d, was equal 10. The predrilled hole in the timber was 13 mm in diameter and the grade of steel plates and bolts was SS400, according to Japanese Industrial Standard (JIS) [17].

The steel side plates were 6 mm and the bolt hole in the steel plate was 14 mm in diameter. The clearance between the steel plate and the timber was 0.5 mm. The displacement between the steel plate and the timber was measured with two displacement transducers. The test was carried out at a constant rate [18] of 1.5 mm/min and, terminated when the load decreased to 80 % of the maximum load or when the bolt failed.

To achieve the information and to calculate the yield strength of DSB by EYT, 6 embedding specimens, parallel to grain were conducted to build a database of embedding strength values. For the embedding strength, the results were calculated using the Japanese standard formulae.

The thickness of its specimen was in the range of the produced glued laminate timber of EGH and the predrilled hole was 13 mm. The dimensions of the embedding specimens according to EN 383 [12] and ASTM D 5764 [10, 11] were 120 mm in length, 120 mm in width and 120 mm in thickness, (Fig. 3). The embedding stress increment parallel to grain was 10–30 MPa/min for the elastic area. Embedding tests parallel to the grain were terminated when the embedding displacement was equal to 5 mm.

Compression tests were carried out on the small clear specimens cut out from same sample (Fig. 1). This was done to compare and analyze the relation between compression strength and embedding strength, and the yield strength of DSB joints can be calculated.

Forty-two compressive specimens were cut out from different laminates of 120 × 20 × 600 mm. The dimension of compressive specimens was 20 mm square in loading section and 40 mm in height (dimensions according the laminate thickness). The compression parallel to the grain tests were conducted based on JIS Z 2101-1994 [18] (Fig. 4). Deformations were measured by displacement transducer, and strain gages of 20-mm length were setup on both sides of specimens.

Compressive tests parallel to the grain were terminated when the maximum load was attained or when the load decreased 80 % of maximum load.

Results and discussion

Yield strength of DSB joints is usually based on the wood embedding strength (f_e) and the fastener yield capacity in bending. Bending deformation of the bolt was observed (Fig. 2) and the yield moment is considered to be the important parameter used in EYT. The initial stiffness (K_s), yield strength (P_y) and ultimate strength (P_u) for DSB test were obtained from the load–displacement relation in the experiment. Yield strengths of DSB test were evaluated by 5 % offset method ($P_{y5\%}$), according to American and Japanese standard code [11–16] (Fig. 5). In this method the line (A) that goes through the points on the curve, corresponding to 10 and 40 % of the maximum load (P_{max}) up to 15-mm displacement according to EN 26891 [19], was moved 5 % of the dowel diameter (d) parallel to the X-direction. The yield strength of 5 % offset method was defined as the intersection of this line and the load–displacement curve. The line (B) that goes through the points on the curve corresponding to 40 and 90 % of P_{max} was moved as tangential to the load displacement curve (B′). The intersection between line A and B′ is defined as yield strength (P_y). Figure 6, illustrated the experimental results and they are located on the plastic zone.

On the whole, the initial stiffness defined by the line A, showed a positive correlation with density (Fig. 7). However, the relation between yield strength and yield strength evaluated by 5 % offset method with density showed a poor relation (Fig. 7).

The DSB joint test used had a wood thickness and dowel diameter ratio of 10. The yield strength of bolt joints was also calculated by the Japanese Standard for structural design based on EYT (Eqs. 1, 2) [20].

$$P_y = C \times f_e \times d \times l \quad (1)$$

$$C = \min[1, (d/l \times (\sqrt{8\gamma/3}))] \quad (2)$$

where l thickness of specimen, d bolt diameter, f_e embedding strength of the wood and C is a constant number determined by failure mode joint configuration. The γ is defined as f/f_e being $f = 235$ N/mm^2 (the steel yield strength) and f_e is the embedding strength value defined for wood type in the Japanese standard code by density. Since the EGH density was scaled out, embedding strength was evaluated according to EC5 [21].

$$f_e = 0.082(1 - 0.01d)\rho_k \quad (3)$$

$$\rho_k = \rho_{AVE} - (K \times SD) \quad (4)$$

where f_e is the embedding strength according to the characteristic density (ρ_k in kg/m^3) and dowel diameter (d), ρ_{AVE} is the mean density from clear specimens of DSB joint test, K constant number indicated in the Japanese code [22] as 2.336 for this study and SD standard deviation.

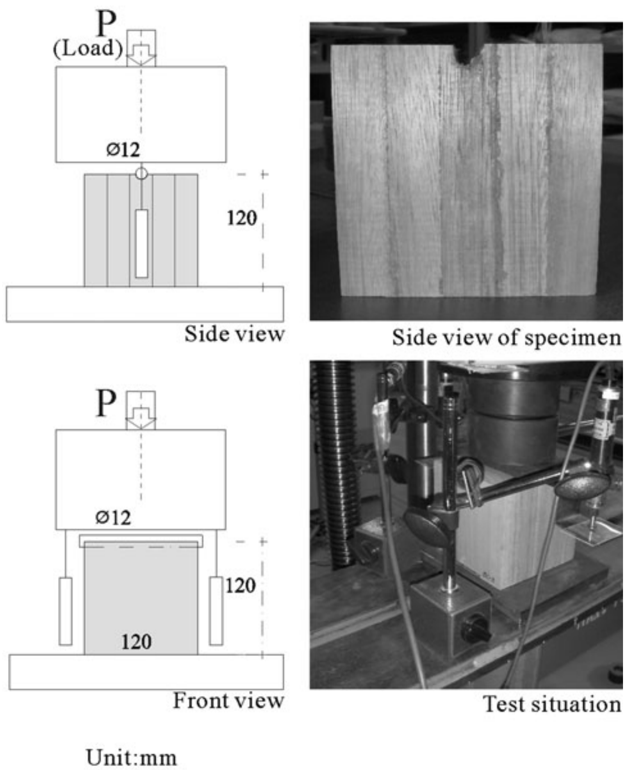


Fig. 3 Embedding test configuration

Fig. 4 Compression test configuration

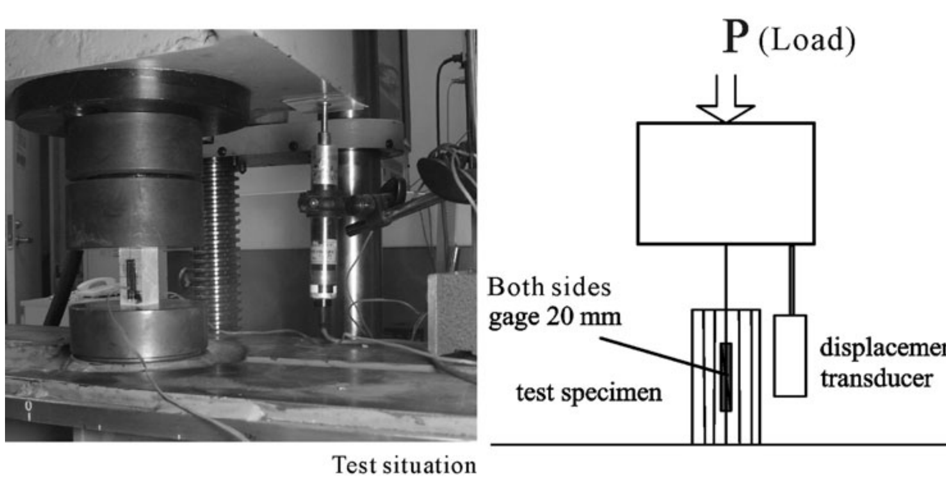


Table 1 shows the results from the experiments, where the yield strength of bolted joints was compared with those calculated from the EYT. The yield strengths obtained from the experiment, as previous studies [23, 24], showed a good agreement with EYT method (Fig. 8). As shown in Fig. 8, there is a closer relation between P_y and P_{yEYT} than $P_{y5\%}$ and P_{yEYT}.

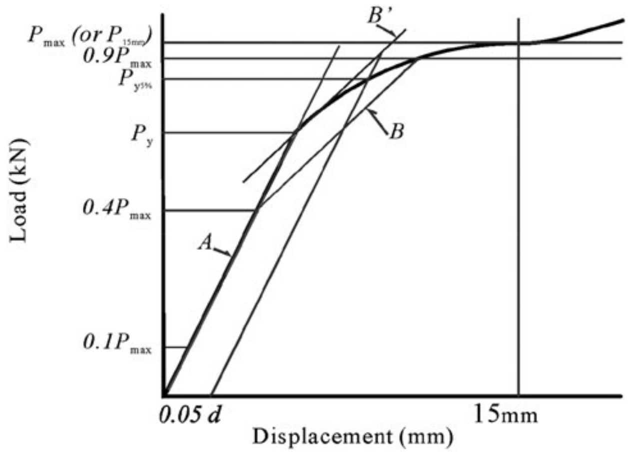


Fig. 5 Evaluation of yield strength in a load–displacement curve. *A* The line which connected the point of 0.1 P_{max} and 0.4 P_{max}. *B* The line which connected the point of 0.4 P_{max} and 0.9 P_{max}. *B′* The line which moved thee line *B* in parallel until it touched the load–displacement curve

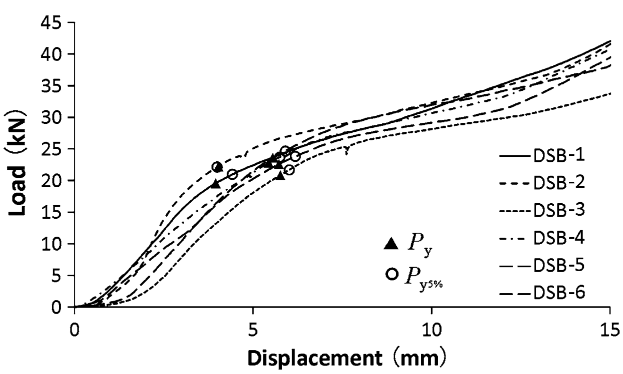


Fig. 6 Load–displacement curves of DSB joint test

Based on these, an important relationship can be observed to exist between experimental yield strength and yield strength obtained from 5 % offset method ($P_{y5\%}$), proving its applicability for these lumber species (EGH).

The yield strength calculated by EYT (P_{yEYT}), is based on the embedding strength obtained as a function of characteristic density (ρ_k). The embedding tests were conducted to verify whether this embedding strength is proper.

The embedding strengths (Fig. 9) were evaluated by 5 % offset method [10, 11] and EN 383 [12] (e.g., Sawata and Yasumura [9]), respectively. In the former method, the line (A) that goes through the points on the curve corresponding to 10 and 40 % of the maximum load (f_{emax}) up to 5-mm displacement was moved 5 % of the dowel diameter (*d*) parallel to the *X*-direction. The embedding strength ($f_{e5\ \%}$) is the intersection of this line and the load–displacement curve. The latter is defined as the maximum load up to 5-mm displacement. The former and the latter methods are expressed as 5 % embedding strength and f_{emax} in this paper, respectively. The line (B) that goes through the points on the curve, corresponding to 40 and 90 % of the maximum load was moved as tangential to the load–displacement curve (B′). The intersection between line A and B′ is defined as yield embedding strength (f_{ey}).

Embedding strength was calculated as follows.

$$f_{e\beta} = P / (d \times t) \tag{5}$$

where f_e is the embedding strength, β is the evaluation method (5 % or 5 mm), P is the load, d is the dowel diameter and t is the thickness of the specimens.

Table 2 shows the results of the embedding test parallel to the grain. Despite the great number of studies reported on the relations between wood or wood-based material and

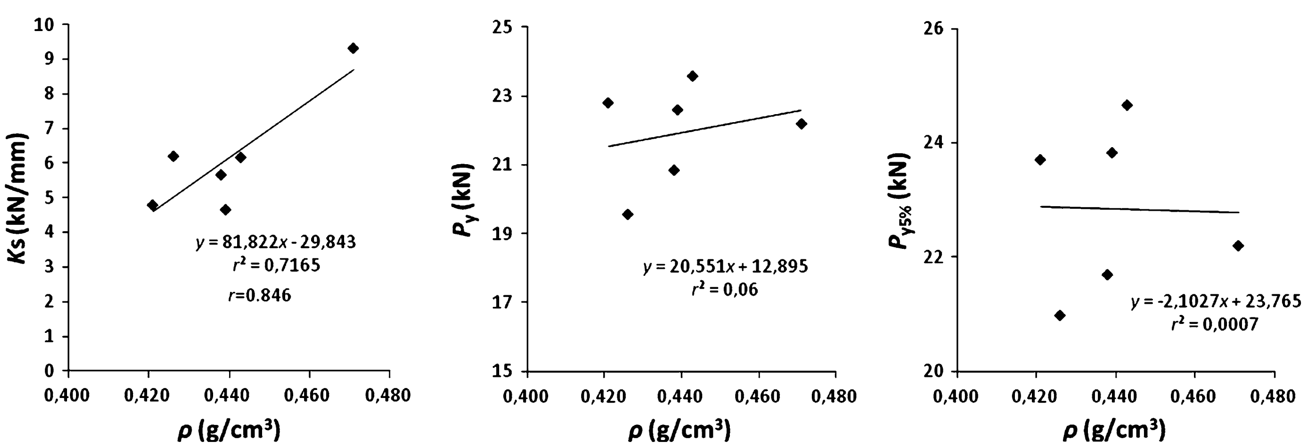


Fig. 7 Results of DSB test—density relation

Table 1 Double shear test results

EGH	ρ (g/cm^3)	MC (%)	P_y (kN)	D_y (mm)	P_{max} (kN)	$P_{y5\%}$ (kN)	P_{yEYT} (kN)	K_s (kN/mm)	P_y/P_{yEYT} (ratio)	$P_{y5\%}/P_{yEYT}$ (ratio)
Name										
DSB-1	0.426	7.182	19.56	3.95	42.03	20.97	19.34	6.205	1.01	1.08
DSB-2	0.471	6.951	22.20	4.03	41.64	22.20		9.311	1.15	1.15
DSB-3	0.438	7.215	20.85	5.77	33.72	21.69		5.653	1.08	1.12
DSB-4	0.421	7.242	22.80	5.44	40.89	23.70		4.805	1.18	1.23
DSB-5	0.443	7.286	23.58	5.55	38.25	24.66		6.170	1.22	1.28
DSB-6	0.439	7.428	22.59	5.72	39.54	23.82		4.647	1.17	1.23
AVE	0.440	7.22	21.93	5.08	39.35	22.84	19.34	6.132	1.13	1.18
SD	0.018	0.16	1.47	0.85	3.09	1.43	0.00			
CV (%)	3.980	2.16	6.69	16.75	7.85	6.27	0.00			
5 % limit			18.50		32.13	19.50	19.34			
ρ_k	0.399									

ρ density, *MC* moisture content, P_y yield strength, D_y yield displacement, P_{max} ultimate strength up to 15 mm according to EN 26891, $P_{y5\%}$ yield strength calculated by 5 % offset according to ASTM D5652 and Japanese Standard, P_{yEYT} yield strength according EYT, K_s stiffness evaluated by 10–40 % P_{max}, *AVE* average, *SD* standard deviation, *CV* coefficient of variance, *5 % limit* 95 % lower limit value on 75 % confidence interval, ρ_k characteristic density

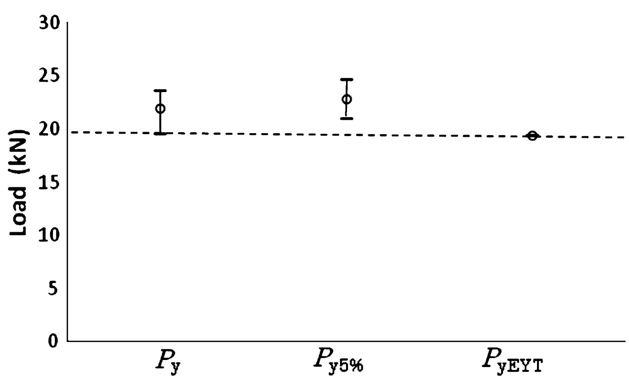


Fig. 8 Compares yield strength respect to theoretical methods. A *circle* of *legend symbol* shows average value. The line of the upper and lower sides of an *error bar* shows the maximum and the minimum

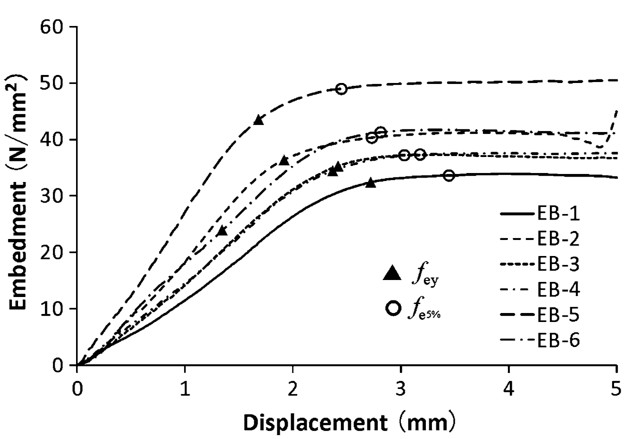


Fig. 9 Embedment-displacement curves of embedding test

bolt diameter for embedding strength, few data on the variance of embedding strength and yield embedding strength have been found. Figure 10 showed a good relation between embedding strength parallel to grain up to f_{emax} and density. This is in good agreement with Sosa Zitto et al. [7]. However, this may be due to abnormal increase in EB-2 test as shown in Fig. 9. Contrary with Sosa Zitto et al. [7], a poor agreement between yield embedding strength (f_{ey}) and embedding strength evaluated by 5 % offset method ($f_{e5\ \%}$) with density were observed (Fig. 10). This may be due to few numbers of specimens and the range of density value was narrow.

Whale et al. [25] conducted a comprehensive investigation for embedding strength on softwood, being one of the basis for dowel-type joints design in EC5, using only the maximum embedding strength and not looking at the yield embedding strength.

In the test results, the embedding strength obtained by $f_{e5\ \%}$ [10, 11] was close to the strength of f_{emax}, and the yield embedding strength (f_{ey}) evaluated by Japanese standard code was a little lower than these. This happened because the 5 % offset method is located at the end of the plastic zone, and constant behaviors were observed up to the end point of 5-mm embedment. This means that the embedding strength of EGH can be calculated by 5 % offset method (this study). However, 5-mm embedment showed a better relation with density contrary to yield embedding strength as illustrate in Fig. 10.

Embedding strengths obtained from the experiment were compared with the embedding strength calculated by EC5 (Fig. 11). Embedding strength calculated by EC5 was close to the average value of yield embedding strength and the minimum value of the embedding strength obtained by 5 % offset method or 5-mm embedment.

The obtained values, which showed an increase of embedding strengths, were applied in EYT formulae. From Fig. 11, it can be observed that f_{emax} and $f_{e5\ \%}$ have a upper value of 12.31 and 11.01 N/mm^2, respectively, proving a

Table 2 Compares embedding strengths from different evaluation methods

EGH	ρ (g/cm^3)	f_{ey} (N/mm^2)	$f_{e5\ \%}$ (N/mm^2)	f_{emax} (N/mm^2)	f_{eEC5} (N/mm^2)	f_{ey}/f_{eEC5} (ratio)	$f_{e5\ \%}/f_{eEC5}$ (ratio)	f_{emax}/f_{eEC5} (ratio)
Name								
EB-1	0.426	32.42	33.62	33.21	28.79	1.126	1.168	1.153
EB-2	0.471	36.39	40.32	46.43		1.264	1.400	1.613
EB-3	0.438	35.33	37.23	37.31		1.227	1.293	1.296
EB-4	0.421	34.47	37.36	37.57		1.197	1.298	1.305
EB-5	0.443	43.50	48.98	50.49		1.511	1.701	1.754
EB-6	0.439	23.96	41.27	41.10		0.832	1.433	1.427
AVE	0.440	34.35	39.80	41.02	28.79	1.19	1.38	1.42
SD	0.018	6.33	5.24	6.41	0			
CV	3.980	18.44	13.17	15.63	0			
5 % limit		19.60	27.55	26.04	28.79			
ρ_k	0.399							

ρ density, f_{ey} yield embedding strength, $f_{e5\ \%}$ embedding strength by 5 % offset method ASTM D5652 and Japanese standard, f_{emax} embedment up 5 mm displacement by EN 383, f_{eEC5} embedding strength by EC5, *EGH Eucalyptus grandis* H., *AVE* average, *SD* standard deviation, *CV* coefficient of variance, *5 % limit* 95 % lower limit value on 75 % confidence interval, ρ_k characteristic density

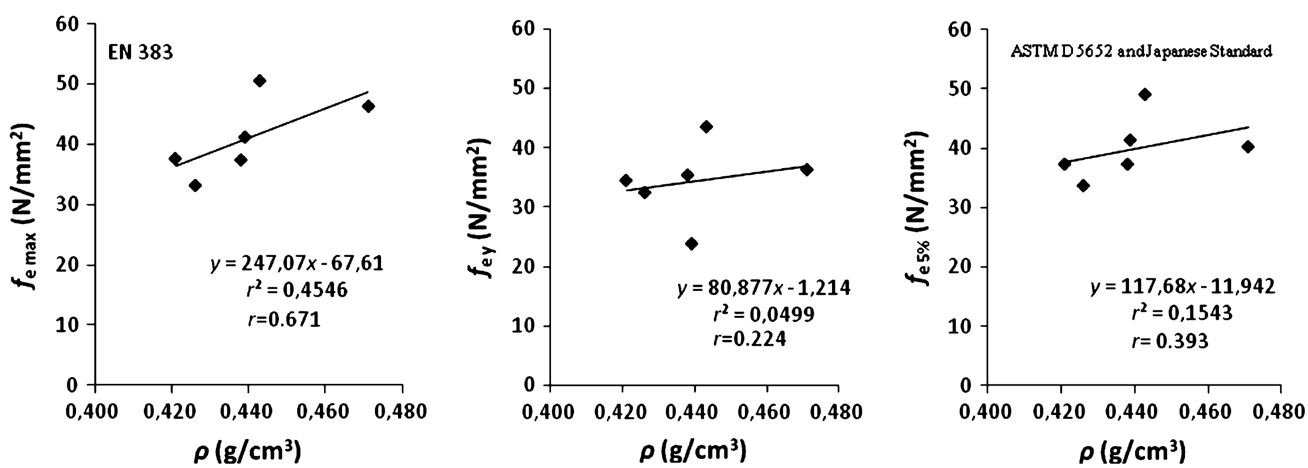


Fig. 10 Results of embedding test—density relation

close and positive approximation to obtain the yield strength by EYT.

However, the absence of huge amount of embedding tests to apply these criteria, compressive tests were proposed to compare the embedding strength with the compressive strength obtained from the compressive tests (e.g., Sawata and Yasumura [9]).

Three compressive specimens were cut out from the lamina of a bolt hole position (Fig. 1). Compressive tests were carried out to obtain a value of compressive strength and relate them with embedding strength value.

The ratio of embedding strength to compressive strength (f_e/f_{cAVE}) and density is shown in Table 3. The ratio of these was about 0.89 times and almost constant, regardless of the evaluation method. From the results described

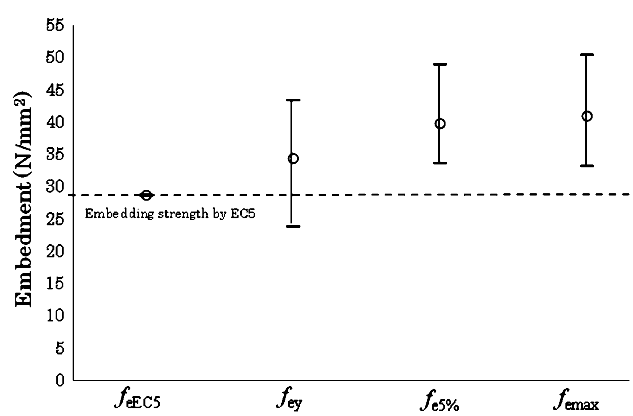


Fig. 11 Embedding strength remaining values. A *circle* of *legend symbol* shows average value. The line of the upper and lower sides of an *error bar* shows the maximum and the minimum

Table 3 Compressive test data from 6 laminate embedding test

EGH	ρ (g/cm^3)	MC (%)	f_{cAVE} (N/mm^2)	E (N/mm^2)	P_{max} (kN)	$f_{e5\,\%}/f_{cAVE}$ (ratio)	f_{emax}/f_{cAVE} (ratio)
Name							
CT-1	0.426	8.50	44.46	11014.38	17.90	0.76	0.75
CT-2	0.471	8.11	51.52	14476.95	20.53	0.78	0.90
CT-3	0.438	8.24	44.66	12199.16	17.87	0.83	0.84
CT-4	0.421	7.91	45.88	13734.93	18.35	0.81	0.82
CT-5	0.443	8.39	45.64	11366.68	18.00	1.07	1.11
CT-6	0.439	8.34	43.97	11681.40	17.58	0.94	0.93
AVE	0.440	8.25	46.02	12412.25	18.37	0.87	0.89
SD	0.018	0.21	2.79	1388.47	1.09		
CV	3.980	2.57	6.06	11.19	5.91		
5 % limit			39.51	9168.78	15.83		

ρ density, f_{cAVE} mean compressive strength from 3 compressive test, E modulus of elasticity, P_{max} maximum load, *EGH Eucalyptus grandis* H., *AVE* average, *SD* standard deviation, *CV* coefficient of variance, *5 % limit* 95 % lower limit value on 75 % confidence interval

above, 5 % and 5-mm embedding strengths can be estimated by the following Eq. 6 [9].

$$f_{emax} = 0.89 f_c \tag{6}$$

where f_{emax} is the embedding strengths (N/mm^2) parallel to the grain evaluated up to 5-mm embedment according EN 383 [12] and f_c is the compressive strength (N/mm^2) parallel to the grain. However, to evaluate the relationship between embedding strength and compressive strength with more accuracy, more tests should be conducted.

Furthermore, other compressive tests were conducted to evaluate the relation between compressive strength and density. Compressive strength (f_c) parallel to the grain was evaluated with a maximum stress according to the Japanese Industrial Standard [18] (Table 4). Figure 12 shows a strong and positive correlation between f_c and ρ.

When the regression line is extended through the origin, it was possible to express the f_e as:

$$f_e = 0.89 f_c = 0.89(81.3\rho - 1.6323) \tag{7}$$

where f_e is the embedding strength (N/mm^2), f_c is the compressive strength (N/mm^2) parallel to the grain and ρ is density (g/cm^3).

Finally, Table 5 compared the yield strength of DSB calculated by EYT applying the embedding strengths based on different evaluation methods. From the yield strength ratios, the evaluation method applying $f_{e5\,\%}$ and f_{emax} provide closer values to experimental DSB yield strength results. Furthermore, the ratio of yield strength evaluated from compressive strengths shows a very close value with a narrow variability than the other yield strength evaluated by EYT.

The average value and variability of $P_{yEYT5\,\%}$ or $P_{yEYT5mm}$ were very close to the yield strength (P_y) or 5 % offset method ($P_{y5\%}$) of experimental results (Fig. 13).

Table 4 Resume of compression parallel test results

EGH	APU Lab.				
	ρ (g/cm^3)	ARW (mm)	MC (%)	E (N/mm^2)	f_c (N/mm^2)
N	42				
AVE	0.52	3.61	12.23	13061	40.98
SD	0.06	1.06	0.47	2722	5.07
CV (%)	11.53	29.36	3.84	20.84	12.37

ρ density, *ARW* annual ring growth, *MC* moisture content, E modulus of elasticity, f_c compression strength, N sample population, *AVE* average, *SD* standard deviation, *CV* coefficient of variance

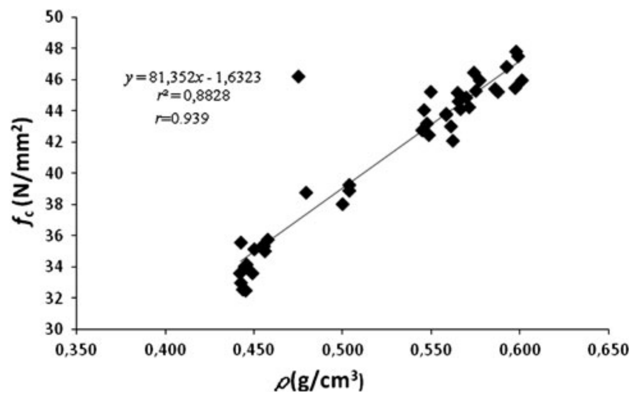


Fig. 12 Compressive strength and density relation

These mean that, comparing the DSB yield strength verifications by EYT with verifications by EYT and applying the $f_{e5\,\%}$ and f_{emax}, the latter provides closer values of yield strengths to experimental results (Table 5) when compared to Sosa Zitto et al. [7]. Also it was possible to provide a very close value of yield strength to experimental results based on compressive strength, as illustrate in Fig. 14.

Conclusions

The conclusions can be summarized as follows:

In the test results of DSB, the yield strength evaluated by Japanese standard code is slightly lower than the yield strength obtained from 5 % offset method.

The yield strengths obtained from the experiment showed a good agreement with the yield strength calculated by EYT method. Especially, the minimum value of experimental yield strengths evaluated by Japanese standard code is very close to the calculated yield strength (P_{yEYT}).

In the test results, the embedding strength obtained by 5 % offset method was close to the strength of 5-mm embedment, and the yield embedding strength evaluated by Japanese standard code was a little lower than these.

Table 5 Compare the yield strength of DSB based on different evaluation methods

EGH	P_y (kN)	$P_{y5\%}$ (kN)	P_{yEYT} (kN)	$P_{yEYT5\ \%}$ (kN)	$P_{yEYT5mm}$ (kN)	P_{yEYTfc} (kN)	$P_{yEYT5\ \%}/P_{yEYT}$ (ratio)	$P_{yEYT5mm}/P_{yEYT}$ (ratio)	P_{yEYTfc}/P_{yEYT} (ratio)
Name									
DSB-1	19.56	20.97	19.34	20.91	20.55	20.71	1.08	1.06	1.07
DSB-2	22.20	22.20		22.90	24.56	21.83	1.18	1.27	1.13
DSB-3	20.85	21.69		22.00	22.02	21.01	1.14	1.14	1.09
DSB-4	22.80	23.70		22.03	22.10	20.58	1.14	1.14	1.06
DSB-5	23.58	24.66		25.23	25.61	21.14	1.30	1.32	1.09
DSB-6	22.59	23.82		23.24	22.94	21.04	1.20	1.19	1.09
AVE	21.93	22.84	19.34	22.72	22.96	21.05	1.17	1.19	1.09
SD	1.47	1.43	0.00	1.47	1.85	0.44			
CV (%)	6.69	6.27	0.00	6.49	8.05	2.07			
5 % limit	18.50	19.50	19.34	19.27	18.65	20.03			

P_y yield strength, P_{yEYTfc} yield strength evaluated by EYT applying f_c, $P_{yEYT5\ \%}$ yield strength evaluated by EYT applying $f_{e5\ \%}$, $P_{yEYT5mm}$ yield strength evaluated by EYT applying f_{emax}, *EGH Eucalyptus grandis* H., *AVE* average, *SD* standard deviation, *CV* coefficient of variance, *5 % limit* 95 % lower limit value on 75 % confidence interval

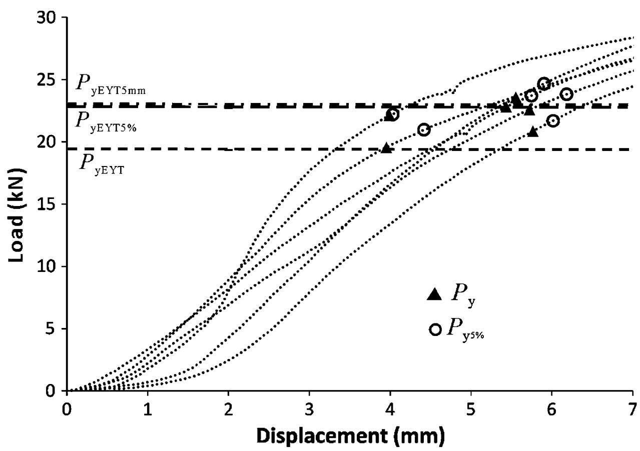


Fig. 13 Remaining values of experimental yield strength and those evaluated by theoretical methods

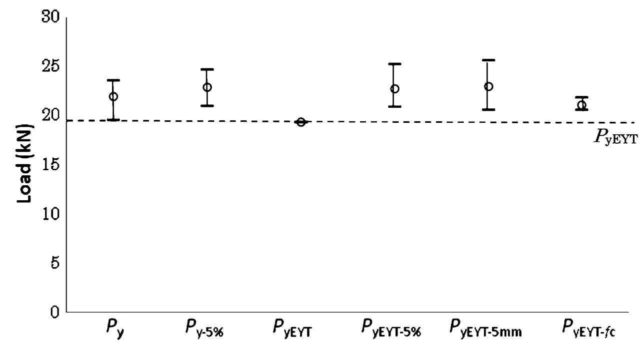


Fig. 14 Remaining values of experimental yield strength and those evaluated by theoretical methods. A *circle* of *legend symbol* shows average value. The line of the upper and lower sides of an *error bar* shows the maximum and the minimum

Embedding strength calculated by EC5 was close to the average value of yield embedding strength and the minimum value of the embedding strength obtained by 5 % offset method or 5-mm embedment.

The ratio of compressive strength to embedding strength was about 0.89 times, and there is a strong and positive correlation between compressive strength and density. Therefore, the embedding strength can be estimated by compressive strength or density.

The yield strength of DSB evaluated from compressive strength is very close to the yield strength calculated by EYT.

The average and variability of the yield strength of DSB calculated by EYT, applying the embedding strengths of experimental results, were very close to the yield embedding strength or 5 % offset method of experimental results.

The results from this study showed a good behavior to structural design with EGH in accordance to the Japanese standard code. However, for a comprehensive use of the Japanese standard code it is necessary to evaluate the yield strength of bolted joints with other dowels' diameters, nails and screws.

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