Experimental Analysis of the Influence of the Fastener Material and Loaded End and Edge Distances on the Embedment Strength Parallel to the Grain in Glued Laminated Timber

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ABSTRACT: Embedment strength is an important parameter that governs the ductile load-carrying capacity of timber joints with dowel-type fasteners. This property is dependent upon several factors, such as the fastener material and the size of the test specimens. Therefore, this paper tested the embedment strength parallel to the grain using smooth steel dowels and densified wood dowels with a diameter (*d*) of 12mm, in glued laminated timber with different loaded end distances (4*d*, 7*d*, 8*d*, 9*d*) and edge distances (2*d*, 3*d*, 4*d*). It was found that the embedment strengths of the specimens using smooth dowels with edge distance of 2*d* were significantly lower than those of the specimens with edge distance of 3*d*, and the embedment strengths of the specimens using smooth steel dowels and densified wood dowels did not show statistically significant difference, when the edge distance of specimens is not less than 3*d*.

KEYWORDS: embedment strength, smooth steel dowel, densified wood dowel, loaded end distance, loaded edge distance

1 – INTRODUCTION

The embedment strength cannot be regarded as a material property, but a system property [1], which depends not only on the wood properties, but also on the surface conditions of the fasteners and their material properties.

There are two test methods to determine the embedment strength. One method is the full-hole test method according to EN 383 [2], which specifies the loaded end distance of the test specimens parallel to the grain as seven times the dowel diameter, and the edge distance of the test specimens parallel to the grain as three times the dowel diameter. The other method is the half-hole test method according to ASTM D5764-97a [3], which specifies the minimum loaded end distance of the test specimens parallel to the grain as the larger of 50 mm or four times the dowel diameter, and the minimum edge distance of the test specimens parallel to the grain as the larger of 25 mm or two times the dowel diameter. The small loaded end and edge distances cause the premature splitting at even smaller embedment deformation. The smaller the ratio of the end and edge distances to the diameter of fasteners, the earlier splitting can occur. Therefore, it is worthwhile to compare the embedment strength parallel to the grain in timber with different loaded end and edge distances.

Compared to steel dowels, wooden dowels have the favorable compatibility of stiffness with the assembled timber members, which reduces the risk of splitting of the assembled timber members. Due to higher mechanical properties, densified wood (DW) has become an alternative to natural wood as wooden fasteners, and DW dowels as environmentally friendly products can be promising fastener alternatives to steel fasteners to develop more sustainable timber structures.

It was found in the experimental study on timber connections loaded parallel to the grain [4] that the splitting of timber members only occurred in the timber connections with steel dowels rather than in the timber connections with DW dowels when the connection geometry met the requirements of minimum geometries specified in Eurocode 5 [5].

Therefore, the embedment tests were performed to explore the effect of loaded end and edge distances on the embedment strength parallel to the grain in timber using DW dowels. In addition, the embedment strengths parallel

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to the grain in timber using smooth steel dowels and DW dowels were compared.

2 – MATERIALS AND METHODS

2.1 MATERIALS

The timber members were glued laminated timber made of Mongolian Scots pine (*Pinus sylvestris var. mongolica Litv*.). The specimens were conditioned in an environment-controlled room at 20℃ and 65% relative humidity until their masses became constant. Their densities ρ_M were measured and the corresponding moisture contents M were measured by using the wood moisture meter. The oven-dry densities ρ_0 were determined by using Equation (1) according to ASTM D2395-17 [6], where the density of water ρ_w is taken as 1000 kg/m^3.

$$\rho_0 = \frac{\rho_M}{1 + 0.01M - 0.009M\dfrac{\rho_M}{\rho_\mathrm{W}}} \tag{1}$$

Figure 1. Fasteners

The average density of the specimens was 522.75 kg/m^3, and the average moisture content was 12.67%. Two types of fasteners with 12 mm diameter (d) were used as shown in Figure 1, i.e., smooth steel dowels made from hot rolled Q235 plain round bars and DW dowels manufactured by compressing the poplar (*Populus tomentosa carriere*) along the radial direction with the compression ratio of 64% following thermo-mechanical densification process.

2.2 SPECIMENTS

The half-hole embedment test configuration was adopted according to ASTM D5764-97a [3], in order to avoid the bending of fasteners as shown in Figure. 2. The embedment test methods in EN 383 [2] and ASTM D5764-97a [3] specify the requirement for loaded end and edge distances of the embedment specimens as shown in Table 1.

Table 1: Dimensions of embedment specimens for dowels

Dimensions	EN 383 [2]	ASTM D5764-97a [3]
L (mm)	7d	max (4d; 50 mm)
W (mm)	6d	max (4d; 50 mm)
t (mm)	1.5d-4d	min (2d; 38 mm)

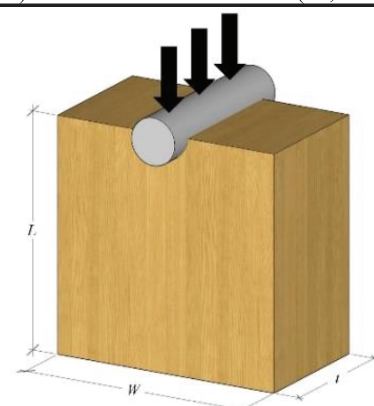

Figure 2. Dimensions of embedment specimen

Six series embedment tests and eight replicates for each series were carried out using 12 mm smooth steel dowels for the specimens with different end distances (4d, 7d, 8d, 9d) and different edge distances (2d, 3d, 4d).

Four series embedment tests and eight replicates for each series were carried out using 12 mm DW dowels for the specimens with different end distances (4d, 7d, 8d, 9d) and different edge distances (2d, 3d).

The series were named as SD/DWD-*Lmd-Wnd*, e.g., SD-*L*4*d*-*W*4*d* denotes the series for the embedment test using 12 mm smooth steel dowels with the specimen length of 4d and width of 4d, i.e., end distance of 4d and edge distance of 2d, as shown in Table 2.

Table 2: Configurations of specimens

Series	Type of fasteners	Length	Width	Thickness	L × W × t (mm)
SD-*L*4*d*-*W*4*d*	Smooth steel dowels	4d	4d	2d	48×48×24
SD-*L*7*d*-*W*4*d*	Smooth steel dowels	7d	4d		84×48×24
SD-*L*7*d*-*W*6*d*	Smooth steel dowels	7d	6d		84×72×24
SD-*L*8*d*-*W*6*d*	Smooth steel dowels	8d	6d		96×72×24
SD-*L*8*d*-*W*8*d*	Smooth steel dowels	8d	8d		96×96×24
SD-*L*9*d*-*W*6*d*	Smooth steel dowels	9d	6d		108×72×24
DWD-*L*4*d*-*W*4*d*	DW dowels	4d	4d		48×48×24
DWD-*L*7*d*-*W*6*d*	DW dowels	7d	6d		84×72×24
DWD-*L*8*d*-*W*6*d*	DW dowels	8d	6d		96×72×24
DWD-*L*9*d*-*W*6*d*	DW dowels	9d	6d		108×72×24

2.3 TEST SETUP

The test setup is shown in Figure. 3. The specimens were loaded at a constant rate of 1.0 mm/min. The deformation of the specimen was measured by using two linear variable differential transformer (LVDT) displacement transducers.

Figure 3. Loading device of test

2.4 TEST METHOD

The ultimate embedment strength $f_{h,u}$ in MPa can be determined by the maximum load F_{max} within the 5 mm deformation according to EN 383 [2], and the yield embedment strength $f_{h,y}$ in MPa can be determined by the yield load F_{yield} using 5% diameter offset method according to ASTM D5764-97a [3] as follows:

$$f_{h,u} = \frac{F_{max}}{dt} \quad (2)$$

$$f_{h,y} = \frac{F_{yield}}{dt} \quad (3)$$

2.5 STATISTICAL ANALYSIS

An analysis of variance (ANOVA) was adopted to assess the statistical significance of the wood density and embedment strengths, and the results were considered to be statistically significant at the 5% level.

3 – RESULTS AND DISCUSSION

3.1 DENSITY

Table 3 lists the test results of the density and moisture content of the specimens. The mean densities for 10 test series did not show any statistically significant differences. Thus, the mean embedment strengths for 10 test series can be compared.

Table 3: Densities and moisture contents of the embedment specimens

Series	Density			
	ρ (kg/m^3)	COV (%)	ρ_0 (kg/m^3)	COV (%)
SD-*L4d*-*W4d*	506.99	4.21	474.35	4.44
SD-*L7d*-*W4d*	514.28	6.67	481.62	7.02
SD-*L7d*-*W6d*	525.69	1.96	492.80	2.07
SD-*L8d*-*W6d*	543.13	8.02	510.27	8.49
SD-*L8d*-*W8d*	532.35	5.09	499.46	5.39
SD-*L9d*-*W6d*	525.18	9.42	492.52	9.94
DWD-*L4d*-*W4d*	509.05	4.36	476.39	4.60
DWD-*L7d*-*W6d*	515.89	2.76	483.12	2.91
DWD-*L8d*-*W6d*	525.00	9.95	492.36	10.49
DWD-*L9d*-*W6d*	529.93	10.78	497.30	11.40

3.2 EMBEDMENT STRESS-DEFORMATION CURVES

Figure 4 shows the embedment stress-deformation curves for the specimens using smooth dowels and DW dowels. The embedment stress-deformation behavior can be first described by almost linear-elastic responses, and then the easement curves describe the passage from the elastic to plastic behavior up to the yield embedment strength. After the ultimate embedment strengths were reached, the embedment stress-deformation behavior shows a softening response.

3.3 EXPERIMENTAL RESULTS

The experimental results are summarized in Table 4, where the mean values of the embedment properties from for each series were reported and their COVs below 15%. The number of replications was relatively sufficient and the range of the COVs was also acceptable. Besides bearing failures, splitting failures also occurred as shown in Figure 5.

Table 4: Experimental results

Series	Embedment strength			
	$f_{h,y}$ (MPa)	COV (%)	$f_{h,u}$ (MPa)	COV (%)
SD-*L4d*-*W4d*	29.24	12.77	30.29	12.66
SD-*L7d*-*W4d*	30.96	8.08	31.21	7.37
SD-*L7d*-*W6d*	38.20	3.15	39.23	3.85
SD-*L8d*-*W6d*	36.88	6.71	37.76	6.96
SD-*L8d*-*W8d*	37.02	7.13	38.81	5.25
SD-*L9d*-*W6d*	35.84	10.12	36.93	9.77
DWD-*L4d*-*W4d*	34.73	7.19	35.07	8.44
DWD-*L7d*-*W6d*	35.16	14.15	35.22	14.06
DWD-*L8d*-*W6d*	37.51	12.31	37.51	12.31
DWD-*L9d*-*W6d*	36.27	11.41	37.32	12.20

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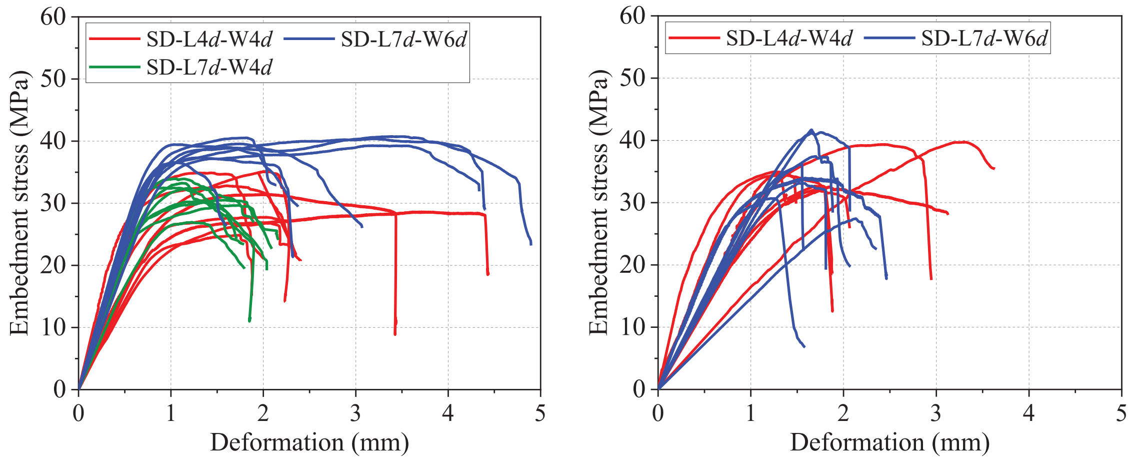
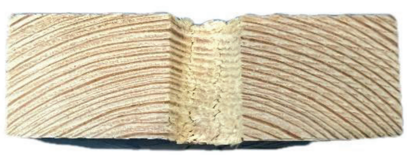


(a)

(b)

Figure 4. Embedment stress-deformation curves for: (a) smooth steel dowels and (b) DW dowels



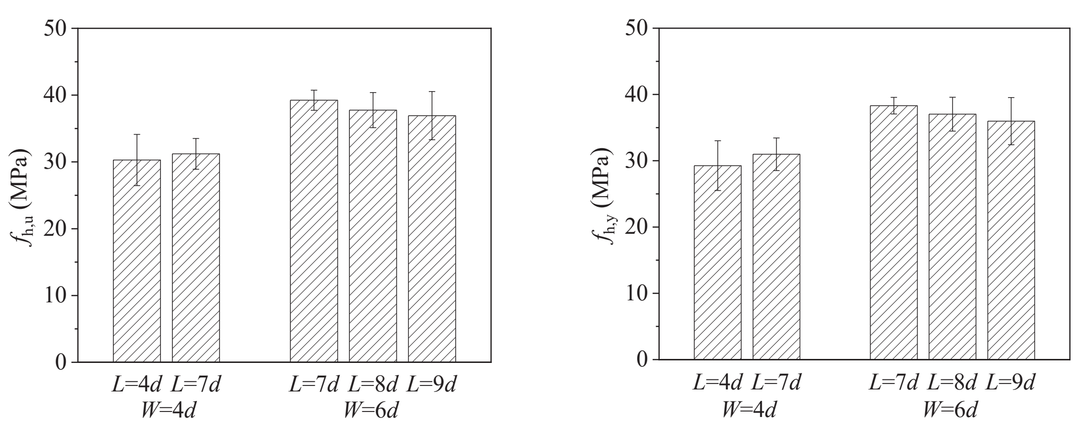
(a) Bearing failures in the specimens using smooth steel dowels in the cross-section view

(b) Bearing failures in the specimens using DW dowels in the cross-section view

(c) Splitting failures in the specimens using smooth steel dowels in the front view

(d) Splitting failures in the specimens using DW dowels in the front view

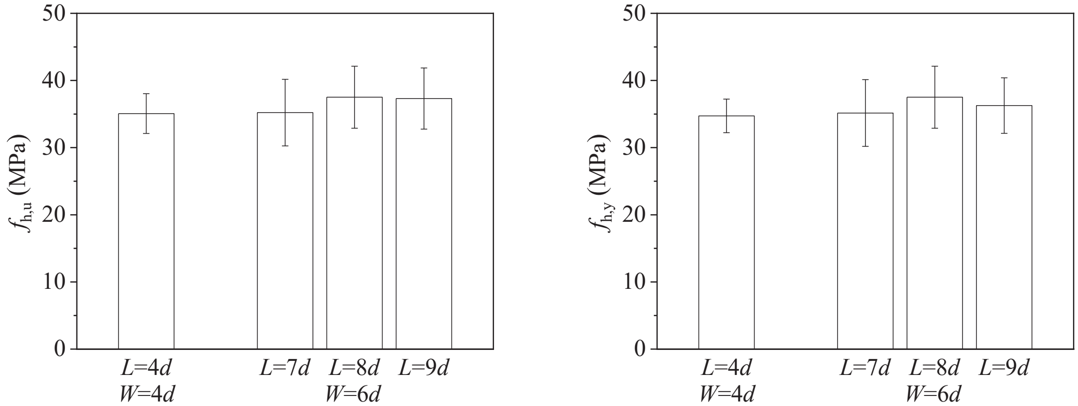
Figure 5. Failure modes in the specimens



(a) Ultimate embedment strengths

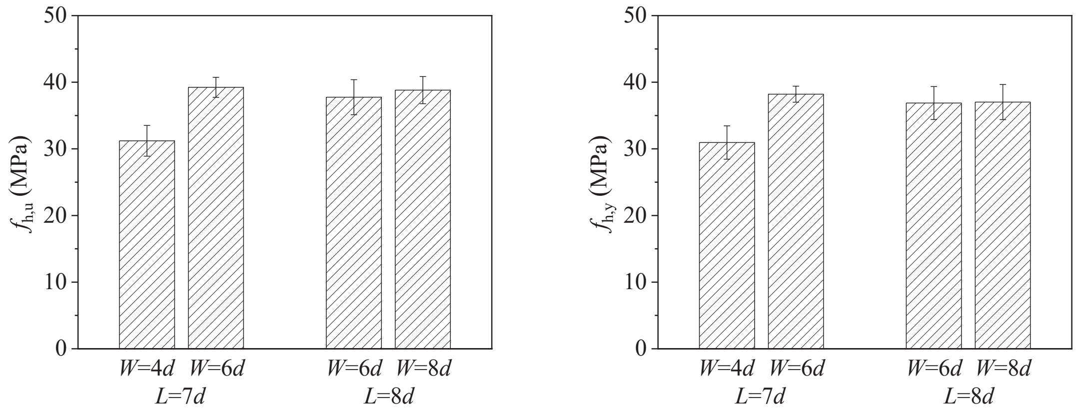
(b) Yield embedment strengths

Figure 6. Embedment strengths of the specimens using smooth steel dowels with different loaded end distances



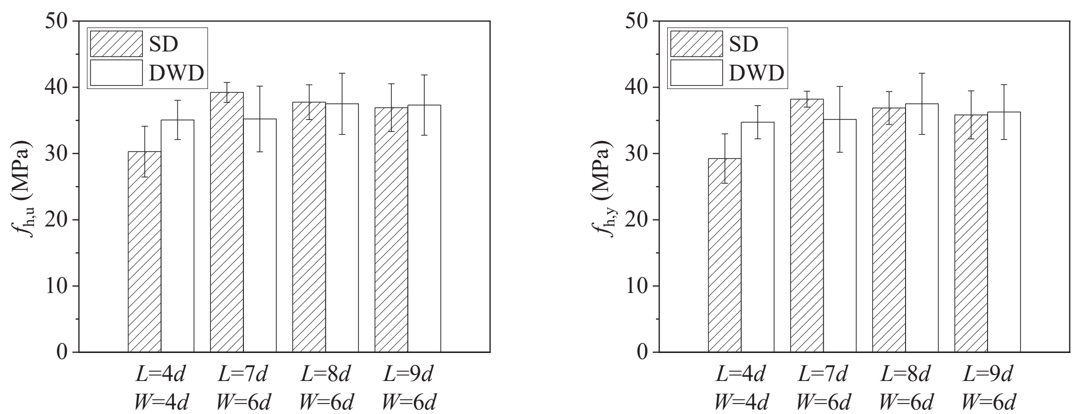
(a) Ultimate embedment strengths *(b) Yield embedment strengths*

Figure 7. Embedment strengths of the specimens using DW dowels with different loaded end and edge distances



(a) Ultimate embedment strengths *(b) Yield embedment strengths*

Figure 8. Embedment strengths of the specimens using smooth steel dowels with different edge distances



(a) Ultimate embedment strengths *(b) Yield embedment strengths*

Figure 9. Embedment strengths of the specimens using smooth steel dowels and DW dowels

3.4 EFFECT OF END DISTANCE

Figure 6 illustrates the embedment strengths of the specimens using smooth steel dowels with different loaded end distances. As the specimen width of 4*d*, i.e., edge distance of 2*d*, the embedment strengths did not show statistically significant difference for the specimens with loaded end distance of 4*d* and 7*d*. Similarly, as the specimen width of 6*d*, i.e., edge distance of 3*d*, the embedment strengths did not show statistically significant

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differences for the specimens with loaded end distances of 7*d*, 8*d*, and 9*d*.

As shown in Figure 7, the embedment strengths of the specimens using DW dowels with different loaded end distances (4*d*, 7*d*, 8*d*, and 9*d*) did not show statistically significant difference. It suggests that the loaded end distance does not affect the embedment strength, when it is not less than 4*d*.

3.5 EFFECT OF EDGE DISTANCE

Figure 8 illustrates the embedment strengths of the specimens using smooth steel dowels with different edge distances. As the specimen length of 7*d*, i.e., loaded end distance of 7*d*, the embedment strengths of the specimens with edge distance of 2*d*, i.e., specimen width of 4*d*, were significantly lower than those of the specimens with edge distance of 3*d*, i.e., specimen width of 6*d*. As the specimen length of 8*d*, i.e., loaded end distance of 8*d*, the embedment strengths of the specimens with edge distance of 3*d*, i.e., specimen width of 6*d*, did not show statistically significant differences with those of the specimens with edge distance of 4*d*, i.e., specimen width of 8*d*.

As shown in Figure 7, the embedment strengths of the specimens using DW dowels with different edge distances of 2*d* and 3*d*, i.e., specimen width of 4*d* and 6*d*, did not show statistically significant difference. It suggests that the edge distance does not affect the embedment strength in timber using DW dowels, when it is not less than 2*d*.

3.6 EFFECT OF FASTENER MATERIALS

Figure 9 illustrate the embedment strengths of the specimens using smooth steel dowels and DW dowels. As the specimen length of 4*d*, i.e., loaded end distance of 4*d*, and the specimen width of 4*d*, i.e., edge distance of 2*d*, the embedment strengths of the specimens using DW dowels were significantly higher than those using smooth steel dowels. Except that, the embedment strengths did not show statistically significant differences for the specimens using DW dowels and smooth steel dowels.

5 – CONCLUSION

The embedment tests parallel to the grain were performed using smooth steel dowels and DW dowels with a diameter (*d*) of 12mm, in glued laminated timber with different loaded end distances (4*d*, 7*d*, 8*d*, 9*d*) and edge distances (2*d*, 3*d*, 4*d*).

The loaded end distance does not affect the embedment strength, when it is not less than 4*d*. The embedment strengths of the specimens using smooth steel dowels with edge distance of 2*d* were significantly lower than those of the specimens with edge distance of 3*d*. The edge distance does not affect the embedment strength in timber using DW dowels, when it is not less than 2*d*. The embedment strengths did not show statistically significant differences for the specimens using DW dowels and smooth steel dowels, when the edge distance of specimens is not less than 3*d*.

More experimental campaigns should be encouraged to further validate those finding in this study and to explore the effect of the thickness of embedment specimens.

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