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Pull-Out Performance of Densified Wood Dowels Embedded Into Glued Laminated Timber

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Abstract

Due to the corrosion of fasteners by water-based preservatives, the preserved timber in outdoor environments can decrease the service life of the metal fasteners. In addition, the segregation of timber members and metal fasteners is also difficult during the demolition of timber structures. Wooden fasteners can be a promising alternative to metal fasteners, because they have favorable resistance against corrosion and are more naturally harmonized with timber members. This paper studied the pull-out performance of dried densified wood (DW) dowels embedded

into glued laminated timber (glulam) parallel to the grain with three different embedded lengths in two ambient environments with a temperature of 20°C and relative humidity (RH) of 65% corresponding to service class 1 and relative humidity of 85% corresponding to service class 2 according to Eurocode 5. The hygroscopic swelling of the dried DW dowels with a long embedded length can provide the friction locking to transfer the axial load comparable to the smooth nails.

Keywords: Pull-out performance; Pull-out strength; Densified wood dowel; Hygroscopic swelling; Moisture content.

Introduction

Metal fasteners are common connectors in timber structures. However, the preserved timber in outdoor environments can decrease the service life of the metal fasteners, due to the corrosion of fasteners by water-based preservatives. Wooden fasteners can be a promising alternative to metal fasteners, because they have favorable resistance against corrosion and are more naturally harmonized with timber members. In fact, wooden fasteners have been successfully used for long time in ancient timber structures, shipbuilding and watermills (Edwards and Kariouk Pecquet du Bellay de Verton 2004). In addition, wooden fasteners do not need to be separated from waste timber components, which contributes to the recycling and reuse of wood.

In practice, hardwood pegs are usually used as reinforcements to mortise and tenon connections in timber frame structures (Bulleit et al. 1999; Schmidt and Daniels 1999; Sandberg et al. 2000; Shanks et al. 2008), to overcome moisture condensing problems from fasteners. Moreover, some exploratory studies on timber-to-timber joints with densified wood (DW) dowels have been performed (Jung et al. 2008; Riggio et al. 2016; El-Houjeyri et al. 2019; Xu et al. 2022a), where DW dowels provided favorable load-carrying capacities of joints.

Besides being subjected to the lateral load perpendicular to the axis of the fasteners, timber joints are usually subjected to the axial load along the axis of the fasteners. Hardwood dowels (Jensen et al. 2001; Kaufmann et al. 2018) or DW dowels (Jung et al. 2010) instead of steel rods were glued into timber members to transfer the axial force. Glued-in wooden dowels can achieve high joint efficiency for moment-resisting joints (Koizumi et al. 2001; Jensen et al. 2002; Jensen et al. 2004).

However, the presence of some adhesives may cause health and environmental impacts. In the environments with higher relative humidity, the plasticization and swelling of adhesives increases the internal stresses, which cause the deterioration of steel-timber epoxy joints (Cavalli et al. 2014). Thus, it is worthwhile to explore all-timber adhesive-free connections.

When wooden dowels dried or with relatively low moisture content are embedded into timber members, the hygroscopic swelling can provide the friction locking to transfer the axial load (Ohuchi et al. 2008; Chang and Nearchou 2015). The shape-recovery effect of DW dowels leads to the persisting expansion and facilitates friction fit with timber substrates. Therefore, the DW dowels can provide greater swelling pressure than hardwood dowels (Grönquist et al. 2019) and contribute to higher pull-out capacity and better long-term performances than hardwood dowels (Mehra et al. 2021).

Chang and Nearchou (2015) performed the pull-out tests on the 12 mm dia. DW dowels with the 40% compression ratio made from western red cedar, embedded into the end grain of spruce, and the pull-out capacity with the 150 mm embedded length was 1.88 kN as the specimens were conditioned for 4 days before the pull-out tests. Mehra et al. (2021) conducted the pull-out tests on the 10 mm dia. DW dowels with the 54% compression ratio made from Scots pine, embedded into the side grain of Scots pine, and the pull-out capacity with the 150 mm embedded length was 3.80 kN as the specimens were conditioned for 45 days before the pull-out tests. The pull-out capacity was improved as the specimens were subjected to the accelerated ageing tests under a series of different wetting and drying cycles.

In some previous studies (Chang and Nearchou 2015; Mehra et al. 2021), the DW was machined to circular dowels with the moisture content of 5-6% after hot compression, and the dowels were then embedded into the timber. Prior to the pull-out tests, the specimens were conditioned in a standard ambient environment with a temperature of 20 ± 2°C and relative humidity of 65 ± 5%, which corresponds to service class 1 according to Eurocode 5 (CEN 2004).

There are limited studies on the pull-out capacities of DW dowels in literature. In order to complete the available experimental results, pull-out tests were carried out on the dried DW dowels embedded into the glued laminated timber (glulam) parallel to the grain with different embedded lengths. Before testing, the specimens had been conditioned in two ambient environments with a temperature of 20°C and relative humidity (RH) of 65% corresponding to service class 1 and relative humidity of 85% corresponding to service class 2 according to Eurocode 5 (CEN 2004).

Materials and Methods

Materials

The DW was manufactured by compressing the poplar (*Populus tomentosa carriere*) with alkali pretreatment along the radial direction at 100°C under a pressure of about 12 MPa for about one day to a target thickness of 18 mm with the compression ratio of 55%. Before compressing, Poplar blocks were immersed in an aqueous solution of mixed 2.5 M NaOH and 0.4 M Na_2SO_3 for 3 days and then boiled for 7 hours, in order to soften the blocks.

The obtained DW blocks were cut first, planned to strips with a target thickness of 13 mm, then dried in the drying oven, and finally machined to the round DW dowels (see Fig. 1) with the diameter d = 12 mm, which is the commonly used diameter in some previous studies on timber joints with DW dowels (Jung et al. 2008; Chang and Nearchou 2015).

Fig. 1. DW dowels.

The density, elastic modulus and tensile strength parallel to the grain of the DW, which had been conditioned in a standard climate room with a temperature of 20°C and relative humidity of 65% until the equilibrium moisture was reached, were measured by Xu et al. (2022b) and are shown in Table 1.

Table 1. Density and some mechanical properties of the DW (Xu et al. 2022b).

Density (kg/m^3)	Modulus of elasticity (MPa)	Tensile strength parallel to the grain (MPa)
1241	13251	164

The substrates were glulam made of Mongolian Scots pine (*Pinus sylvestris var. mongolica Litv.*) with a cross-section of 100 mm × 70 mm. They were first conditioned in a standard climate room with a temperature of 20°C and relative humidity of 65% until the equilibrium moisture was reached, and then the density was measured. The mean density ρ was 487.50 kg/m^3 (COV = 5.37%). The moisture contents of the substrates were measured by the wood moisture meter, and the mean moisture content H was 12.65% (COV = 3.33%). Finally, the 12 mm dia. boreholes were drilled.

Specimen Preparations

A total of six series were designed, including three embedded lengths l = 96 mm, 120 mm and 144 mm, which corresponded to 8d, 10d and 12d, and two ambient environments with a temperature of 20°C and relative humidity of 65% corresponding to service class 1 and relative humidity of 85% corresponding to service class 2 according to Eurocode 5 (CEN 2004). The minimum anchorage length for glued-in rods was the maximum value of $0.5d^2$ and $10d$ according to DIN 1052 (DIN 2008), and thus the series with a $10d$ embedded length was taken as the reference, where the shorter embedded length of $8d$ and the longer embedded length of $12d$ were also adopted for the tests in this study.

The series were named as DX-12/20, where D8-12 denoted the series with the $8d$ embedded length and conditioned at a temperature of 20°C and relative humidity of 65% corresponding to 12% moisture content in timber, and D12-20 denoted the series with the $12d$ embedded length and conditioned at a temperature of 20°C and relative humidity of 85% corresponding to 20% moisture content in timber.

The configurations of the test series are summarized in Table 2 and the schematic diagram of the borehole in the specimen is shown in Fig. 2. After the dry DW dowels were embedded into the glulam substrates, the specimens were conditioned in a corresponding climate room until the masses of the specimens became constant to allow for the hygroscopic swelling of the dried DW dowels for tight-fitting.

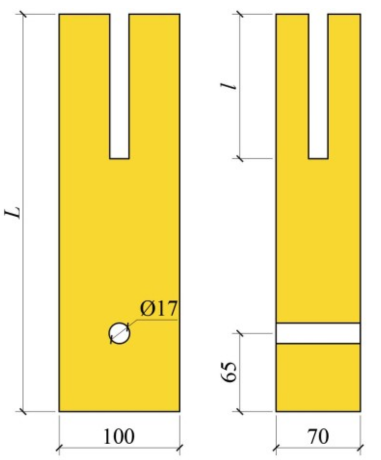


Fig. 2. Schematic diagram of the borehole.

Pull-Out Tests

The pull-out tests were carried out under a constant displacement rate of 2.0 mm/min in a 100 kN electromechanical universal testing machine, and a load cell was used to record the applied load, as shown in Fig. 3. Two linear voltage displacement transducers (LVDTs) were used to measure the relative displacements between the DW dowel and the substrate. The DW dowel was wrapped tightly by the grip, which was contact with the probes of the LVDTs, and there was no slip between the DW dowel and the grip.

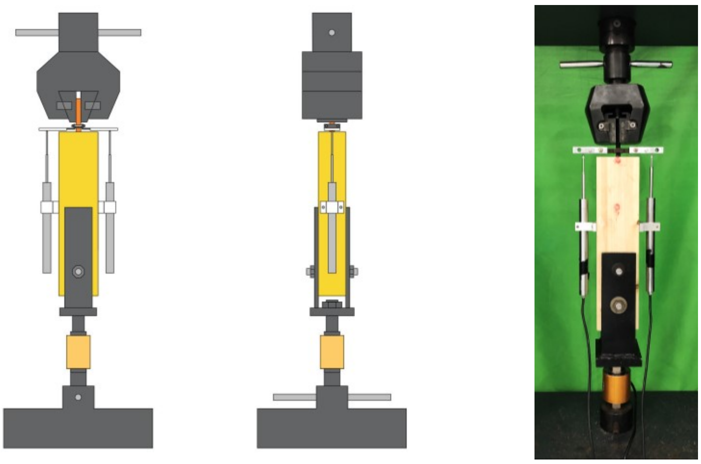


Fig. 3. Test set-up.

The slip modulus K_s is defined as the inclination of the linear approximation from the elastic part in the load-slip curve, and the maximum load is defined as the pull-out capacity F_{ax} as shown in Fig. 4. The pull-out strength W is defined using Eq. (1) below:

$$W = \frac{F_{ax}}{l} \quad (1)$$

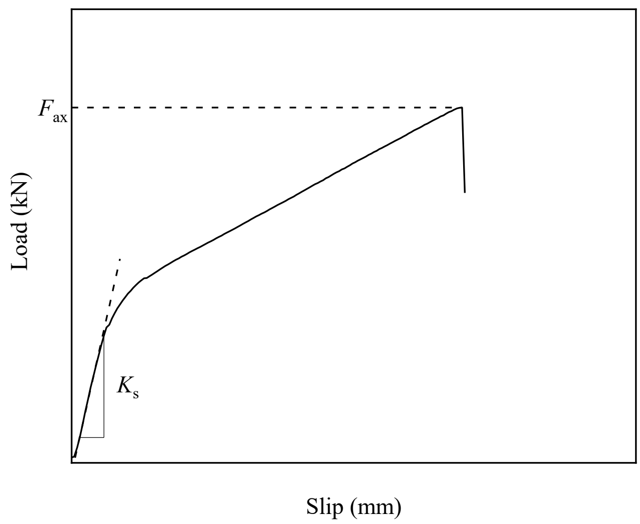


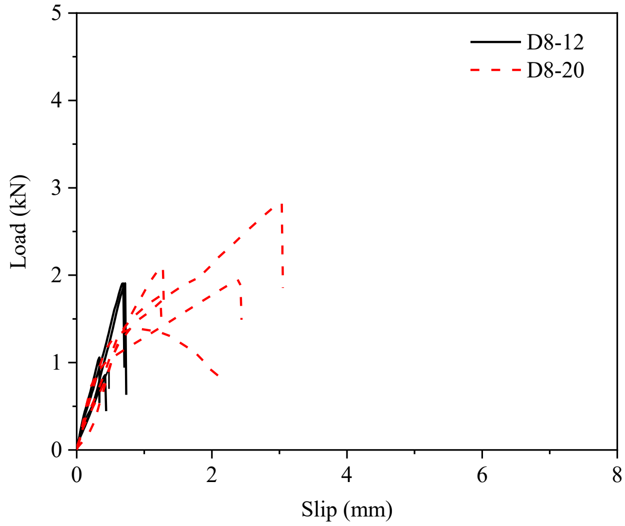
Fig. 4. Load-slip curve with the associated parameters.

Results and Discussion

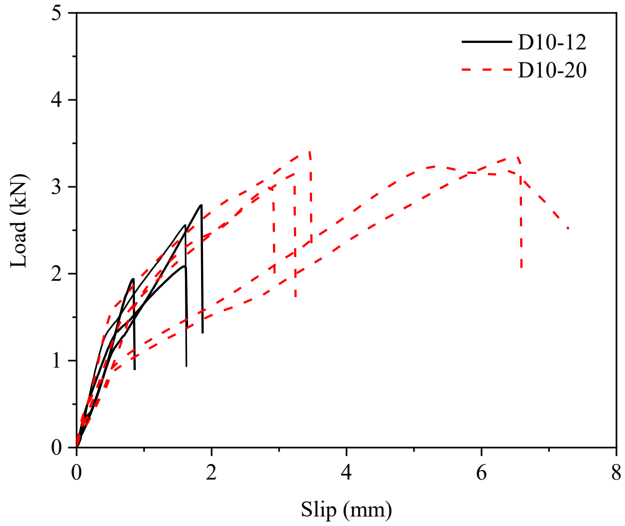
Influence of the Moisture Content

Fig. 5 shows the load-slip curves of the specimens. For the series D8-12 specimens, the loads almost linearly increased with the slips until the maximum loads were reached. For the specimens of other series, the load-slip behaviours were characterised by approximate bi-linear curves until the maximum loads were reached.

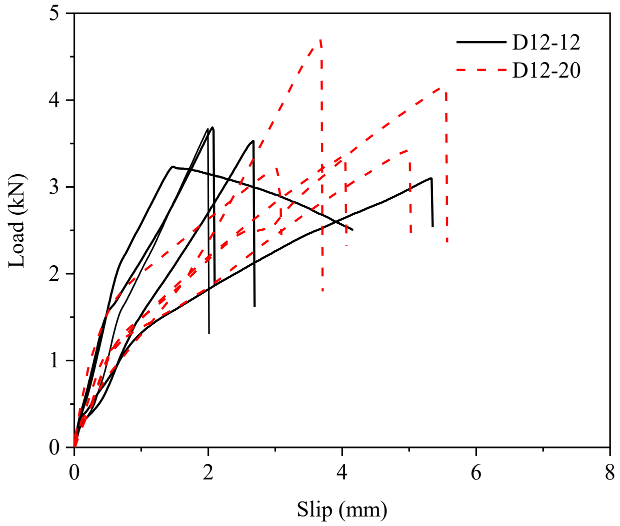
T-test with $p < 0.05$ was performed to evaluate the statistical significance for the pull-out performances of the DW dowels under two ambient environments. The slip moduli had no significant differences. For the specimens with the 10*d* embedded length, the pull-out strengths significantly increased with the increasing moisture content. For the specimens with the 8*d* and 12*d* embedded lengths, the pull-out strengths had no significant differences under two ambient environments.


D8-12
D8-20
Load (kN)
Slip (mm)
0
1
2
3
4
5
0
2
4
6
8

(a)


D10-12
D10-20
Load (kN)
Slip (mm)
0
1
2
3
4
5
0
2
4
6
8

(b)


D12-12
D12-20
Load (kN)
Slip (mm)
0
1
2
3
4
5
0
2
4
6
8

(c)

Fig. 5. Load-slip curves of the pull-out tests: (a) series with the 8*d* embedded length; (b) series with the 10*d* embedded length; and (c) series with the 12*d* embedded length.

Table 2. Configurations of the specimens

Series	Dowel diameter d (mm)	Substrate length L (mm)	Embedded length l (mm)	Ratio of length to diameter (l/d)	Conditioned environment	Duration (days)
D8-12		280	96	8		
D10-12		330	120	10	20°C and 65% RH	10
D12-12	12	385	144	12		
D8-20		280	96	8		
D10-20		330	120	10	20°C and 85% RH	16
D12-20		385	144	12		

Table 3. Summary of the pull-out test results

Series	ρ		H		K_s		F_{ax}		W	
	Mean (kg/m^3)	COV (%)	Mean (%)	COV (%)	Mean (kN/mm)	COV (%)	Mean (kN)	COV (%)	Mean (N/mm)	COV (%)
D8-12	491.37	3.43	12.53	0.92	2.53	23.01	1.33	39.74	13.88	39.74
D10-12	505.40	4.95	12.51	1.34	2.56	24.15	2.31	15.32	19.24	15.32
D12-12	479.51	7.42	12.38	0.73	2.61	39.10	3.44	7.69	23.91	7.69
D8-20	492.60	5.78	20.37	0.64	2.61	29.66	2.01	26.68	20.95	26.68
D10-20	484.90	4.38	19.69	4.53	1.93	40.73	3.23	4.85	26.92	4.85
D12-20	471.22	5.41	20.28	0.28	2.46	34.60	3.78	16.76	26.23	16.76

Influence of the Embedded Length

Table 3 summarises the experimental results. An analysis of variance (ANOVA) with $p < 0.05$ was performed to evaluate the statistical significance for the pull-out performances of the DW dowels with different embedded lengths. The slip moduli had no significant differences. Under the ambient environment with a temperature of 20°C and relative humidity of 65%, the pull-out strengths almost linearly increased when the embedded length increased from 8*d* to 12*d*. This could suggest that the pull-out strength would depend on the embedded length, under the ambient environment with a temperature of 20°C and relative humidity of 65%.

Under the ambient environment with a temperature of 20°C and relative humidity of 85%, the pull-out strengths of the specimens with the 10*d* embedded length were significantly greater than those for the specimens with the 8*d* embedded length, while the pull-out strengths had no significant differences for the specimens with the 10*d* and 12*d* embedded lengths. This could imply that the pull-out strengths almost remained constant when the embedded length was larger than 10*d*, under the ambient environment with a temperature of 20°C and relative humidity of 85%. It could be because under the ambient environment with a higher relative humidity, the higher swelling force would be induced, which could cause micro-cracks on the timber hole walls and then would affect the frictions. This assertion would need to be confirmed by further research on the specimens with longer embedded lengths.

Pull-Out Strength

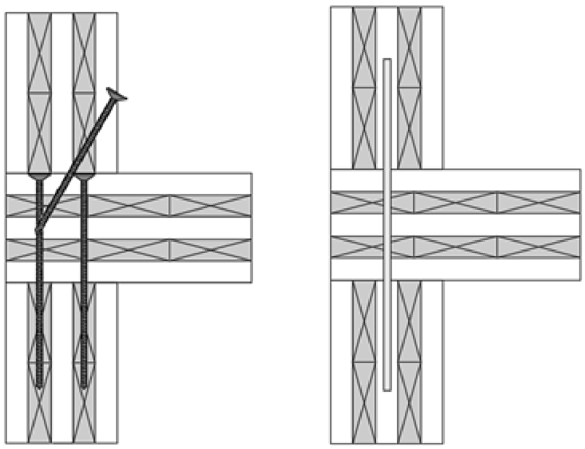
In order to assess the potential of the DW dowels, their pull-out strengths were compared to those of the end-grain nails and self-tapping screws driven parallel to the grain into spruce (*Picea glauca*), which are summarized in Table 4 from the experimental results reported by Teng et al. (2018).

Table 4. Experimental results of the pull-out tests reported by Teng et al. (2018)

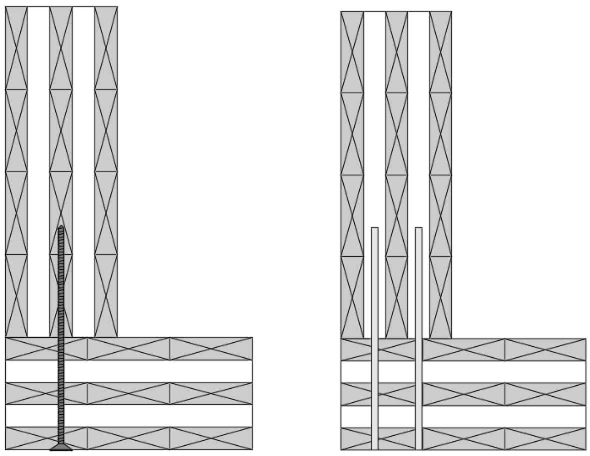
Fasteners	d (mm)	l (mm)	ρ (kg/m^3)	H (%)	W (N/mm)
Smooth nails	2.5	30	440	12.6	11.09
Self-tapping screws	4.0	30	450	13.1	74.85

The pull-out strengths of the DW dowels were greater than those of the end-grain smooth nails, and the pull-out strengths of the DW dowels with the 12d embedded length attained about 30% of those of the end-grain self-tapping screws.

The DW dowels have the practice potential instead of self-tapping screws for connecting a cross-laminated timber (CLT) floor to walls or connecting two CLT walls together as shown in Fig. 6. In this case, DW dowels are embedded into the narrow faces of CLT walls, i.e. driven into the laminates parallel to the grain in CLT walls.



(a)



(b)

Fig. 6. Practice potential of DW dowels instead of self-tapping screws for connecting: (a) CLT floor to walls; and (b) CLT wall to wall.

Conclusions

This paper presented the pull-out performances of the 12 mm dia. dry DW dowels embedded into the glulam parallel to the grain with different embedded lengths under two ambient environments with a temperature of 20°C and relative humidity of 65% corresponding to service class 1 and relative humidity of 85% corresponding to service class 2 according to Eurocode 5.

Under two ambient environments, the slip moduli had no significant differences. Only for the specimens with the 10*d* embedded length, the pull-out strengths significantly increased with the increasing moisture content.

With different embedded lengths, the slip moduli of the specimens had no significant differences. Under the ambient environment with a temperature of 20°C and relative humidity of 65%, the pull-out strengths almost linearly increased with the increasing embedded length. This could suggest that the pull-out strengths would depend on the embedded length, under the ambient environment with a temperature of 20°C and relative humidity of 65%. Under the ambient environment with a temperature of 20°C and relative humidity of 85%, the pull-out strengths of the specimens significantly increased when the embedded length increased from 8*d* to 10*d*, and had no significant differences when the embedded length changed from 10*d* and 12*d*. This could imply that the pull-out strengths almost remained constant when the embedded length was larger than 10*d*, under the ambient environment with a temperature of 20°C and relative humidity of 85%.

In the case of the 12*d* embedded length, the tight-fitting of the 12 mm dia. dry DW dowels showed about twice the pull-out strengths of the 2.5 mm dia. end-grain smooth nails, and attained about 30% of the pull-out strengths of the 4 mm dia. end-grain self-tapping screws. DW dowels can be a promising alternative to metal fasteners, particularly in environments with high and varying moisture contents. The further research should be focused on the pull-out performances of longer dry DW dowels and their explorations for connecting the CLT components instead of the self-tapping screws.

Acknowledgments

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Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request, with the listed items as density, moisture content and pull-out performance.

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