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1 **Pull-Out Performance of Densified Wood Dowels Embedded** 2 **Into Glued Laminated Timber**

3 Bo-Han Xu¹; Yi-Ge Zhao²; Kong-Bin Yu³; Abdelhamid Bouchair⁴; Binsheng Zhang⁵

4 ¹ Associate Professor, State Key Laboratory of Coastal and Offshore Engineering, Ocean
5 Engineering Joint Research Center of Dalian University of Technology – University of Western
6 Australia, Dalian University of Technology, Dalian 116024, People’s Republic of China.
7 Corresponding author, Email: bohanxu@dlut.edu.cn

8 ² Master student, State Key Laboratory of Coastal and Offshore Engineering, Ocean Engineering
9 Joint Research Center of Dalian University of Technology – University of Western Australia,
10 Dalian University of Technology, Dalian 116024, People’s Republic of China. E-mail:
11 zyg@mail.dlut.edu.cn

12 ³ Master student, State Key Laboratory of Coastal and Offshore Engineering, Ocean Engineering
13 Joint Research Center of Dalian University of Technology – University of Western Australia,
14 Dalian University of Technology, Dalian 116024, People’s Republic of China. E-mail:
15 yukongbin@mail.dlut.edu.cn

16 ⁴ Professor, Université Clermont Auvergne, Clermont Auvergne INP, Centre National de la
17 Recherche Scientifique, Institut Pascal, F-63000 Clermont-Ferrand, France. Email:
18 abdelhamid.bouchair@uca.fr

19 ⁵ Professor, Department of Civil Engineering and Environmental Management, School of
20 Computing, Engineering and Built Environment, Glasgow Caledonian University, Glasgow G4
21 0BA, Scotland, UK. Email: Ben.Zhang@gcu.ac.uk

22 **Abstract**

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

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

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

38 **Introduction**

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

48 In practice, hardwood pegs are usually used as reinforcements to mortise and
49 tenon connections in timber frame structures (Bulleit et al. 1999; Schmidt and Daniels
50 1999; Sandberg et al. 2000; Shanks et al. 2008), to overcome moisture condensing

51 problems from fasteners. Moreover, some exploratory studies on timber-to-timber
52 joints with densified wood (DW) dowels have been performed (Jung et al. 2008;
53 Riggio et al. 2016; El-Houjeyri et al. 2019; Xu et al. 2022a), where DW dowels
54 provided favorable load-carrying capacities of joints.

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

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

66 When wooden dowels dried or with relatively low moisture content are
67 embedded into timber members, the hygroscopic swelling can provide the friction
68 locking to transfer the axial load (Ohuchi et al. 2008; Chang and Nearchou 2015). The
69 shape-recovery effect of DW dowels leads to the persisting expansion and facilitates
70 friction fit with timber substrates. Therefore, the DW dowels can provide greater
71 swelling pressure than hardwood dowels (Grönquist et al. 2019) and contribute to

72 higher pull-out capacity and better long-term performances than hardwood dowels
73 (Mehra et al. 2021).

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

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

90 There are limited studies on the pull-out capacities of DW dowels in literature. In
91 order to complete the available experimental results, pull-out tests were carried out on
92 the dried DW dowels embedded into the glued laminated timber (glulam) parallel to

93 the grain with different embedded lengths. Before testing, the specimens had been
94 conditioned in two ambient environments with a temperature of 20°C and relative
95 humidity (RH) of 65% corresponding to service class 1 and relative humidity of 85%
96 corresponding to service class 2 according to Eurocode 5 (CEN 2004).

97 **Materials and Methods**

98 *Materials*

99 The DW was manufactured by compressing the poplar (*Populus tomentosa carriere*)
100 with alkali pretreatment along the radial direction at 100°C under a pressure of about
101 12 MPa for about one day to a target thickness of 18 mm with the compression ratio
102 of 55%. Before compressing, Poplar blocks were immersed in an aqueous solution of
103 mixed 2.5 M NaOH and 0.4 M Na₂SO₃ for 3 days and then boiled for 7 hours, in
104 order to soften the blocks.

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



110

111 **Fig. 1.** DW dowels.

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

116 **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 |

117 The substrates were glulam made of Mongolian Scots pine (*Pinus sylvestris var.*
 118 *mongolica Litv.*) with a cross-section of 100 mm × 70 mm. They were first
 119 conditioned in a standard climate room with a temperature of 20°C and relative
 120 humidity of 65% until the equilibrium moisture was reached, and then the density was
 121 measured. The mean density ρ was 487.50 kg/m³ (COV = 5.37%). The moisture
 122 contents of the substrates were measured by the wood moisture meter, and the mean
 123 moisture content H was 12.65% (COV = 3.33%). Finally, the 12 mm dia. boreholes
 124 were drilled.

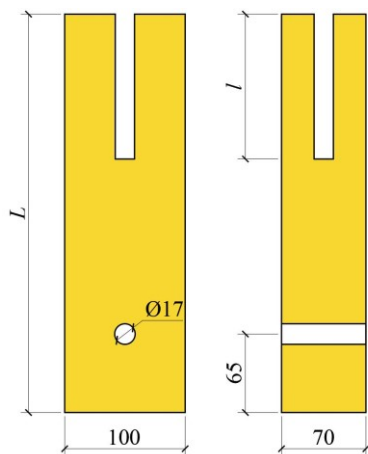
125 ***Specimen Preparations***

126 A total of six series were designed, including three embedded lengths $l = 96$ mm, 120
 127 mm and 144 mm, which corresponded to $8d$, $10d$ and $12d$, and two ambient
 128 environments with a temperature of 20°C and relative humidity of 65% corresponding
 129 to service class 1 and relative humidity of 85% corresponding to service class 2
 130 according to Eurocode 5 (CEN 2004). The minimum anchorage length for glued-in

131 rods was the maximum value of $0.5d^2$ and $10d$ according to DIN 1052 (DIN 2008),
132 and thus the series with a $10d$ embedded length was taken as the reference, where the
133 shorter embedded length of $8d$ and the longer embedded length of $12d$ were also
134 adopted for the tests in this study.

135 The series were named as DX-12/20, where D8-12 denoted the series with the $8d$
136 embedded length and conditioned at a temperature of 20°C and relative humidity of
137 65% corresponding to 12% moisture content in timber, and D12-20 denoted the series
138 with the $12d$ embedded length and conditioned at a temperature of 20°C and relative
139 humidity of 85% corresponding to 20% moisture content in timber.

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

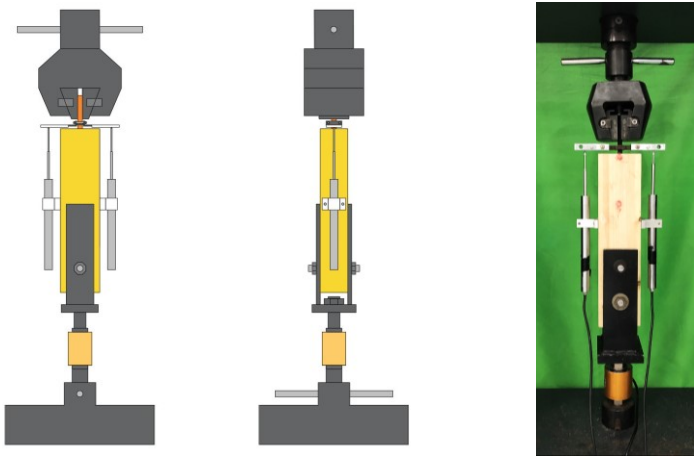


146

147 **Fig. 2.** Schematic diagram of the borehole.

148 **Pull-Out Tests**

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

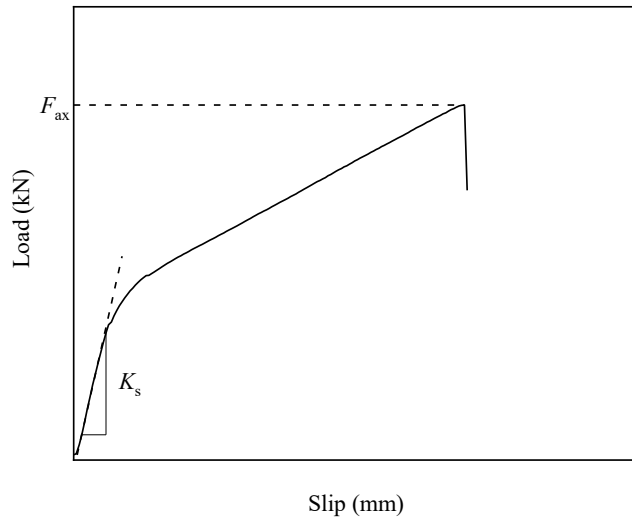


156
157 **Fig. 3.** Test set-up.

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

161 (1) below:

162
$$W = \frac{F_{ax}}{l} \tag{1}$$



163

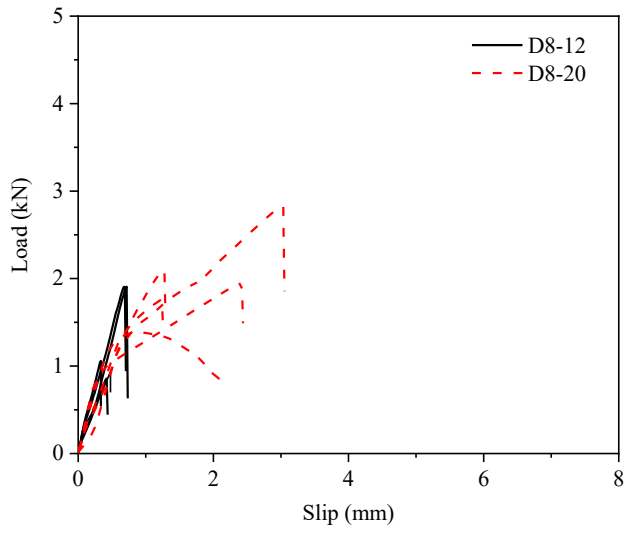
164 **Fig. 4.** Load-slip curve with the associated parameters.

165 **Results and Discussion**

166 *Influence of the Moisture Content*

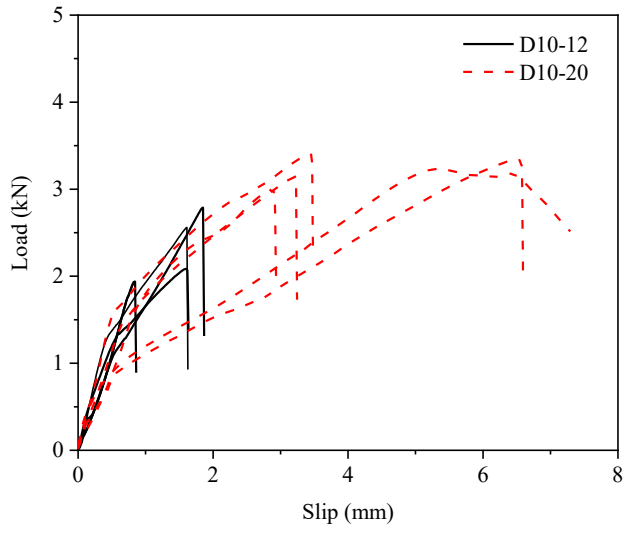
167 Fig. 5 shows the load-slip curves of the specimens. For the series D8-12 specimens,
 168 the loads almost linearly increased with the slips until the maximum loads were
 169 reached. For the specimens of other series, the load-slip behaviours were
 170 characterised by approximate bi-linear curves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

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



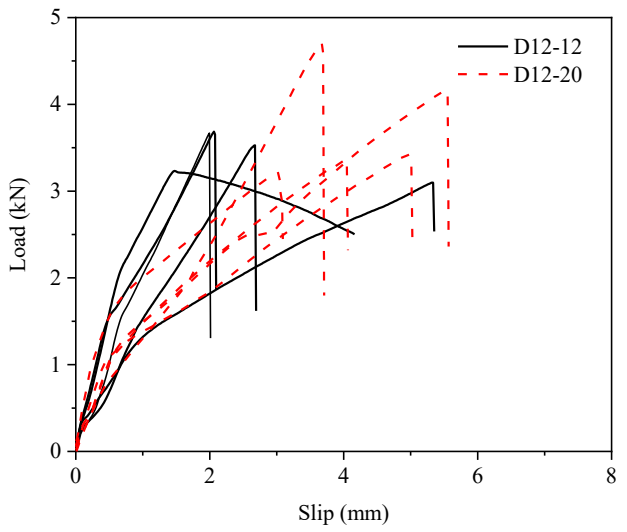
177

178 (a)



179

180 (b)



181

182 (c)

183 **Fig. 5.** Load-slip curves of the pull-out tests: (a) series with the $8d$ embedded length;

184 (b) series with the $10d$ embedded length; and (c) series with the $12d$ embedded length.

185

186 **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 | 12 | 280 | 96 | 8 | 20°C and 65% RH | 10 |
| D10-12 | | 330 | 120 | 10 | | |
| D12-12 | | 385 | 144 | 12 | | |
| D8-20 | | 280 | 96 | 8 | 20°C and 85% RH | 16 |
| D10-20 | | 330 | 120 | 10 | | |
| D12-20 | | 385 | 144 | 12 | | |

187 **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 |

188

189

190 ***Influence of the Embedded Length***

191 Table 3 summarises the experimental results. An analysis of variance (ANOVA) with
192 $p < 0.05$ was performed to evaluate the statistical significance for the pull-out
193 performances of the DW dowels with different embedded lengths. The slip moduli
194 had no significant differences. Under the ambient environment with a temperature of
195 20°C and relative humidity of 65%, the pull-out strengths almost linearly increased
196 when the embedded length increased from $8d$ to $12d$. This could suggest that the
197 pull-out strength would depend on the embedded length, under the ambient
198 environment with a temperature of 20°C and relative humidity of 65%.

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

210 ***Pull-Out Strength***

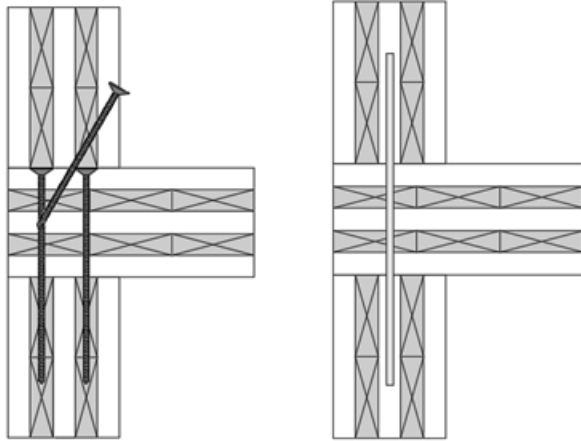
211 In order to assess the potential of the DW dowels, their pull-out strengths were
212 compared to those of the end-grain nails and self-tapping screws driven parallel to the
213 grain into spruce (*Picea glauca*), which are summarized in Table 4 from the
214 experimental results reported by Teng et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

215 **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 |

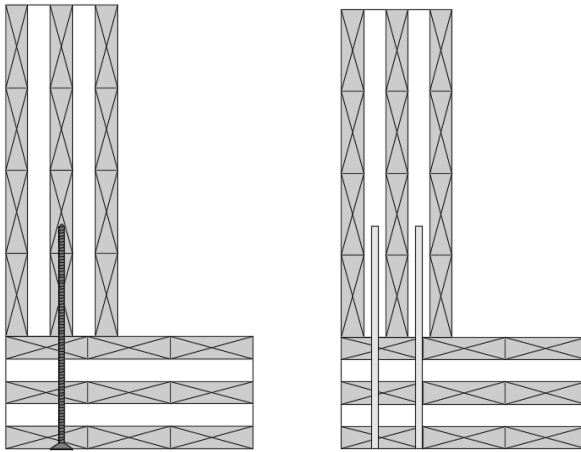
216 The pull-out strengths of the DW dowels were greater than those of the
217 end-grain smooth nails, and the pull-out strengths of the DW dowels with the $12d$
218 embedded length attained about 30% of those of the end-grain self-tapping screws.

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



224

225 (a)



226

227 (b)

228 **Fig. 6.** Practice potential of DW dowels instead of self-tapping screws for connecting:

229 (a) CLT floor to walls; and (b) CLT wall to wall.

230 **Conclusions**

231 This paper presented the pull-out performances of the 12 mm dia. dry DW dowels

232 embedded into the glulam parallel to the grain with different embedded lengths under

233 two ambient environments with a temperature of 20°C and relative humidity of 65%

234 corresponding to service class 1 and relative humidity of 85% corresponding to

235 service class 2 according to Eurocode 5.

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

239 With different embedded lengths, the slip moduli of the specimens had no
240 significant differences. Under the ambient environment with a temperature of 20°C
241 and relative humidity of 65%, the pull-out strengths almost linearly increased with the
242 increasing embedded length. This could suggest that the pull-out strengths would
243 depend on the embedded length, under the ambient environment with a temperature of
244 20°C and relative humidity of 65%. Under the ambient environment with a
245 temperature of 20°C and relative humidity of 85%, the pull-out strengths of the
246 specimens significantly increased when the embedded length increased from $8d$ to
247 $10d$, and had no significant differences when the embedded length changed from $10d$
248 and $12d$. This could imply that the pull-out strengths almost remained constant when
249 the embedded length was larger than $10d$, under the ambient environment with a
250 temperature of 20°C and relative humidity of 85%.

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

257 dowels and their explorations for connecting the CLT components instead of the
258 self-tapping screws.

259 **Acknowledgments**

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261 Foundation of China under the grant No. 51878114.

262 **Data Availability**

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

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