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Pull-Out Performance of Timber Joints with Glued-In Densified Wood Dowels

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Abstract

Densified wood dowel is worth to be regarded as an alternative rod for the timber joints with glued-in rods, because it is more naturally harmonized with timber members, and has better resistance against corrosion and lower thermal conductivity than steel rod. This paper compared the pull-out performances of the timber joints with glued-in densified wood (DW) dowels and threaded steel rods loaded parallel to the grain 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. In service class 1, the pull-out capacity of the glued-in DW dowels having an anchorage length of 10 times the dowel diameter was close to 75% of that of the glued-in threaded steel rods. The impact of service environment was found to be greater for the timber joints with glued-in threaded steel rods than the timber joints with glued-in DW dowels.

Keywords: Pull-out performance; Densified wood dowels; Glued-in rods; Threaded steel rods; Moisture content.

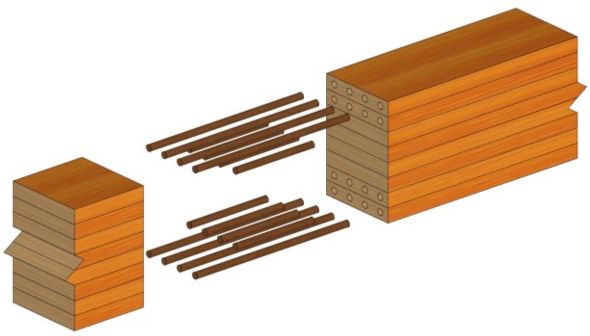
Introduction

As indicated by the name of timber joints with glued-in rods, the rods are glued into the timber members using the adhesive and can efficiently transfer the axial load in the timber structures. The rods are surrounded by timber and can provide the aesthetical appearance and protection from fire. The adhesive should demonstrate a good gap-filling ability and develop a strong bond between the rod and timber, resulting in the timber becoming the weakest link of the joint (Tlustochowicz et al. 2011), and thus this type of joint can offer high strength and stiffness and becomes popular for implementing in the new structures and strengthening of historical buildings.

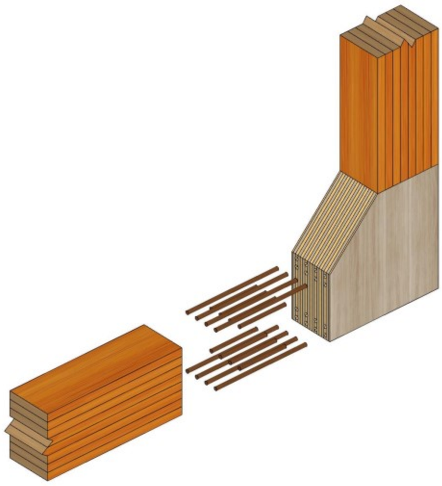
The mechanical performances of timber joints with glued-in rods are related to the adhesives and both adherents (rod and timber). Threaded steel rods (Parida et al. 2013; Xu et al. 2020) or ribbed rebars (Yeboah et al. 2011; Ling et al. 2014) are common rods in practice, due to their high strength and stiffness. The fiber-reinforced polymer (FRP) rods are alternative ones, due to their excellent resistance against corrosion, together with other advantages such as higher strength-to-weight ratio and lower thermal conductivity (Zhu et al. 2017; Tannert et al. 2017).

However, the separation of bonded steel or FRP rods from timber members after service life is difficult and causes waste disposal problem. Wooden dowels are available rods used in timber joints with glued-in rods, which are easily cut with the timber members for the end-of-life disposal, and contribute to the recycling and reuse of wood resources.

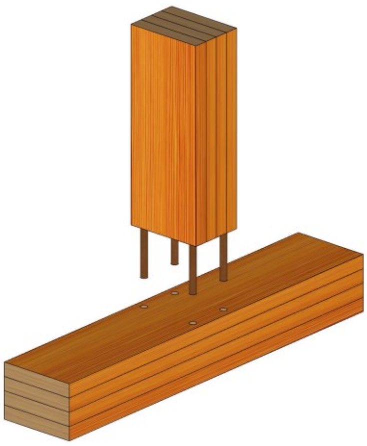
About two decades ago, a series of tests were conducted by Koizumi et al. (1998a, 1998b) to determine the pull-out capacities of the glued-in hardwood dowels with the diameters of 8 mm, 12 mm, 16 mm and 20 mm glued into wood members with the anchorage lengths of 4, 6, 8 and 10 times the dowel diameters. Due to relatively low tensile strengths of hardwoods, some joints failed due to fractures of dowels. Furthermore, structural joints with glued-in hardwood dowels were explored in the applications to end joints of glulam beams (Komatsu et al. 1997; Jensen et al. 2004) shown in Fig. 1(a), corner joints of glulam frames (Jensen et al. 2002) shown in Fig. 1(b) and post-sill joints (Koizumi et al. 2001a) shown in Fig. 1(c), and could achieve high joint efficiency.



(a)



(b)



(c)

Fig. 1. Structural joints with glued-in hardwood dowels: (a) end joints of glulam beams; (b) corner joints of glulam frames; and (c) post-sill joints.

In order to delay the fractures of dowels, densified wood (DW) dowels can be adopted instead of hardwood dowels, because of relatively high tensile characteristics. Jung et al. (2010) performed the pull-out tests on the DW dowels of Japanese cedar and the hardwood dowels of maple glued into spruce laminated timber members using one-component polyurethane adhesive, and found that the pull-out capacity of the glued-in DW dowel was about 1.6 times higher than that of the hardwood dowel, in the case of the anchorage length of 10 times the dowel diameter.

In the timber joints with glued-in rods, epoxy based (EPX) and polyurethane based (PUR) adhesives are commonly used. Koizumi et al. (2001b) found that the flexible PUR with large anchorage lengths contributed to better pull-out capacities than the EPX adhesives, in the joints with glued-in hardwood dowels. For the PUR adhesives with large anchorage lengths, with the increase of the glue-line thickness between 0.25 mm and 1.5 mm, the pull-out capacities increased. However, no significant differences were found for the glue-line thicknesses between 1 mm and 1.5 mm for the EPX adhesives (Koizumi et al. 2001b). It is worth noting that there are many adhesives available of each type, and thus characterizing an adhesive only by terms like EPX or PUR is not sufficient.

Kaufmann et al. (2018) investigated the possible substitution of “synthetic” adhesives with the “natural” adhesive based on renewable resources, to bond hardwood dowels into wood members. Joints with glutine-based and casein-based “natural” adhesives achieved similar pull-out capacities to those with the “synthetic” two-component EPX (Wevo-Spezialharz EP 32 S with Wevo-Härter B 22 TS) and PUR (Loctite VN 3146 Purbond) adhesives under laboratory conditions (50% relative humidity at 23°C).

All the above-mentioned investigative results were obtained under the laboratory environments and corresponded to service class 1 characterized by a moisture content no larger than 12% in timber members according to Eurocode 5 (CEN 2004). However, the timber joints with glued-in rods can also be implemented in service class 2 characterized by a moisture content of up to 20% in timber members according to Eurocode 5 (CEN 2004).

Martín-Gutiérrez et al. (2017) assessed the pull-out performances of the 12 mm dia. threaded steel rods glued into hardwood (chestnut) with a two-component epoxy adhesive (HILTI HIT-RE 500), subjected to extreme climatic cycles of temperature and humidity. The results indicated that the accelerated weathering cycles caused the losses of 12.12% in the stiffness and 13.93% in the pull-out capacity for the joints with usual anchorage lengths, say 10 times the rod diameters, compared to the joints subjected to ambient environments with a temperature of 20°C and relative humidity of 65% corresponding to service class 1. Similar results were found for the 12 mm dia. threaded steel rods glued into softwood with a two-component epoxy adhesive (HILTI HIT-RE 500) by Otero-Chans et al. (2018).

The effect of moisture content is severe for the timber joints with glued-in hardwood dowels with the glutine-based "natural" adhesive (Kaufmann et al. 2018), where the pull-out capacities of the glued-in hardwood dowels in a climatic chamber (95% relative humidity at 30°C) for 96 hours decreased by 65% compared to the joints under the laboratory conditions (50% relative humidity at 23°C).

There were limited studies on the pull-out performances of DW dowels glued into timber members, particularly in humid environments. It is worthwhile to compare the pull-out performances of timber joints with glued-in DW dowels and threaded steel rods. In this study, pull-out tests on the DW dowels glued parallel to the grain of the timber members were carried out to determine the effects of the anchorage lengths and service environments corresponding to service classes 1 and 2. At the same time, the timber joints with glued-in threaded steel rods were also tested as the reference.

Materials and Methods

Materials

The densified wood (DW) was produced by compressing the poplar (*Populus tomentosa carriere*) with alkali pretreatment along the radial direction at 100°C under a pressure of 12 MPa for one day to a target thickness of 18 mm from an initial thickness of 40 mm with the compression ratio of 55%. Before compressing, poplar blocks were immersed in an aqueous solution by mixing 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 firstly cut into strips, and then planed to a target thickness of 13 mm. Thereafter, the DW strips were divided into two groups. One group of strips were dried in the drying oven, and then machined to 12 mm dia. smooth DW dowels, and they were denoted as the dried DW dowels. The other group of strips were conditioned in a standard climate room with a temperature of 20°C and relative humidity of 65% until the equilibrium moisture content was reached, and then machined to 12 mm dia. smooth DW dowels, and they were denoted as the normal 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 content was reached, were measured by Xu et al. (2022) and are shown in Table 1.

Table 1. Density, elastic modulus and tensile strength of the DW (Xu et al. 2022).

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. The strength class of glulam was TC_T24 according to the Chinese Standard for Design of timber structures (2017), corresponding to a characteristic bending strength of 24 MPa. They were first conditioned in a standard climate room with a temperature of 20°C and relative humidity of 65% until the equilibrium moisture content was reached, and then the density was measured. The mean density ρ was measured as 492.12 kg/m^3 (COV = 6.23%), with the mean moisture content H as 12.55% (COV = 2.89%) measured by using the wood moisture meter. The threaded steel rods with strength grade 10.9 were adopted to avoid the failures of the steel rods.

For the joints with glued-in rods, the adhesive should make sure that the adhesive bond will not be the weakest link of the joint. In this study, a two-component epoxy (HILTI HIT-RE 100 HC) was used to bond the DW dowels or threaded steel rods to timber members. The observations from the preliminary tests confirmed that the failures were the localized timber shear failures around the DW dowels or threaded steel rods. It suggests that this type adhesive can develop a strong bond with both adherends in the joints with glued-in rods.

Specimen Preparations

A total of seven series were designed, including three anchorage lengths of 96 mm, 120 mm and 144 mm and two ambient environments. One environment had a temperature of 20°C and relative humidity of 65% corresponding to service class 1, while the other one had a temperature of 20°C and relative humidity of 85% corresponding to service class 2 according to Eurocode 5 (CEN 2004). The configurations of the test series are summarized in Table 2.

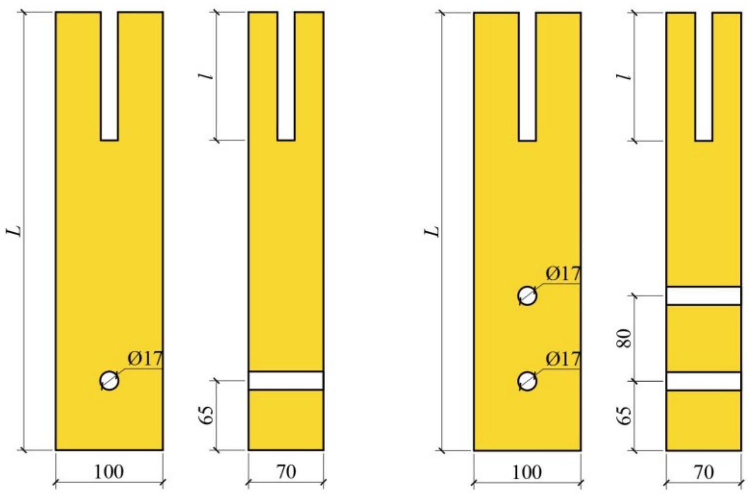
The specimens with the glued-in DW dowels consisted of two timber members and one DW dowel. Fig. 2 shows the schematic diagrams of the boreholes. 16 mm dia. blind holes were predrilled parallel to the grain to maintain a glued-line thickness of 2 mm. Additional 17 mm dia. holes at the other ends of the specimens were predrilled to attach to the testing apparatus using the bolted connections. The method of predrilling two lateral holes was used for the adhesive injection as indicated in the previous studies (Kohl et al. 2020; Xu et al. 2020). The adhesive was injected through the lower lateral hole until it flowed out from the upper lateral hole, and two lateral holes were finally sealed. Five duplicate specimens were prepared for each series.

Table 2. Specimen configurations

Series	Rod material	Diameter d (mm)	Substrate length L (mm)	Anchorage length l (mm)	Ratio of length to diameter (l/d)	Conditioned environment
DG8-12-N	Normal DW		280	96	8	
DG8-12	Dried DW		280	96	8	
DG10-12	Dried DW		330	120	10	20°C and 65% RH for 16 days
DG12-12	Dried DW	12	385	144	12	
BG10-12	Threaded steel rod		410	120	10	
BG10-20	Threaded steel rod		410	120	10	20°C and 65% RH for 8 days and
DG10-20	Dried DW		330	120	10	then 20°C and 85% RH for 16 days

Table 3. Summary of the pull-out test results

Series	H		K_s		F_u		V_u	
	Mean (%)	COV (%)	Mean (kN/mm)	COV (%)	Mean (kN)	COV (%)	Mean (mm)	COV (%)
DG8-12-N	12.24	1.20	21.43	13.27	23.09	9.87	1.17	10.22
DG8-12	12.33	0.93	25.51	10.36	25.18	10.36	0.90	6.52
DG10-12	12.28	1.21	33.61	10.39	34.54	7.60	1.05	10.75
DG12-12	12.29	1.36	33.62	16.39	34.55	8.70	1.03	4.72
BG10-12	12.33	0.93	107.48	4.43	46.14	4.17	0.60	19.41
BG10-20	20.29	0.96	58.92	24.37	37.05	5.73	0.94	19.12
DG10-20	20.08	1.04	28.34	31.94	29.08	12.83	1.31	7.99



(a) (b)

Fig. 2. Schematic diagrams of the boreholes: (a) timber joint specimen with glued-in DW dowels; and (b) timber joint specimen with glued-in threaded steel rods.

For the series DG8-12-N specimens, the normal DW dowels were first glued into the timber members over an 8*d* anchorage length, and then conditioned at a temperature of 20°C and relative humidity of 65% for 16 days before the pull-out tests.

For the series DG8-12, DG10-12 and DG12-12 specimens, the dried DW dowels were first glued into the timber members over three anchorage lengths of 8*d*, 10*d* and 12*d*, and then conditioned at a temperature of 20°C and relative humidity of 65% for 16 days before the pull-out tests.

For the series BG10-12 specimens, the threaded steel rods were first glued into the timber members over a 10*d* anchorage length, and then conditioned at a temperature of 20°C and relative humidity of 65% for 16 days before the pull-out tests.

For the series BG10-20 and DG10-20 specimens, the threaded steel rods and dried DW dowels were first glued into the timber members over a 10*d* anchorage length, then conditioned at a temperature of 20°C and relative humidity of 65% for 8 days, and finally conditioned at a temperature of 20°C and relative humidity of 85% for 16 days before the pull-out tests.

The masses of all the specimens became constant after being conditioned in a corresponding climate for 16 days. The moisture contents of the substrates were then measured by using the wood moisture meter.

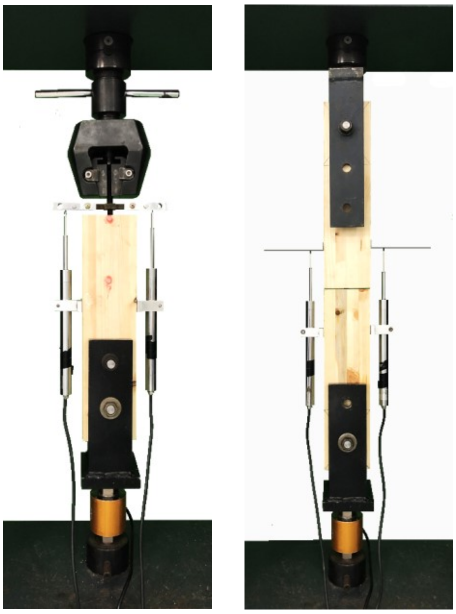
Pull-Out Tests

Fig. 3(a) illustrates the experimental set-up for the specimens with the glued-in threaded steel rods. The steel rod was clamped by the jig, which was connected to the test rig. Considering the greater pull-out load in order to avoid the failure of the end joint, the timber member was attached through two bolts to the steel plates, which were connected to the load cell fixed to the testing machine. Two linear voltage displacement transducers (LVDTs) were used to measure the relative displacements between the steel rod and the timber member.

Due to the great slippage between the DW dowel and the jig, the DW dowel cannot be directly clamped by the jig as the steel rod, and thus a symmetrical experimental set-up was designed to test the specimens with the glued-in DW dowels as shown Fig. 3(b), where two LVDTs were used to measure the relative displacements between two timber members and half the obtained value was regarded as the slip between the DW dowel and the timber member.

However, avoiding initial eccentricity should be of particular concern. The difference between the recorded slips by the two LVDTs could be used to assess the eccentricity during the tests. Different test set-ups were used for the specimens with glued-in DW dowels and glued-in threaded steel rods, and the test set-ups could affect the test results.

In the previous studies on the timber joints with glued-in rods, the constant displacement rate was generally between 0.6 mm/min and 5.0 mm/min (Ling et al. 2014; Gonzalez et al. 2016; Kaufmann et al. 2018; Grunwald et al. 2019; Muciaccia 2019; Bouchard et al. 2021). Hence, in this study, the pull-out tests were carried out at a constant displacement rate of 2.0 mm/min in a 100 kN electromechanical universal testing machine, where the moveable lower platform was connected to a load cell to record the applied load.



(a) (b)

Fig. 3. Test set-up: (a) timber joint specimen with the glued-in threaded steel rods; and (b) timber joint specimen with the glued-in DW dowels.

Here, V_u was the ultimate slip corresponding to the ultimate load which was defined as the pull-out capacity (F_u). The slip modulus (K_s) was calculated as the secant slope of the line connecting two load points at $0.1F_u$ and $0.4F_u$. An analysis of variance (ANOVA) with $p < 0.05$ was performed to evaluate the statistical significance.

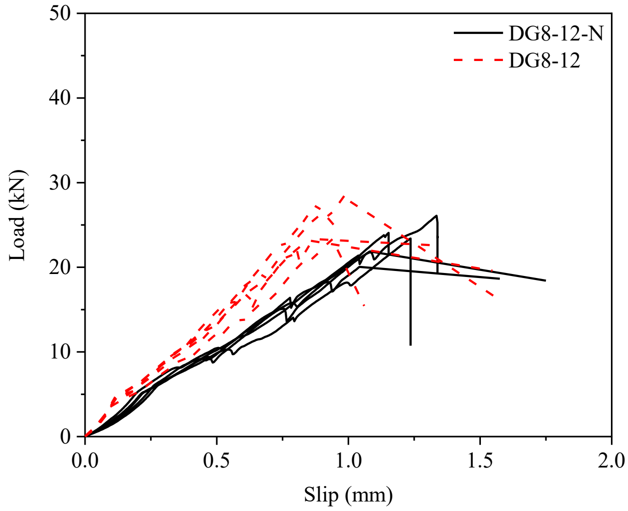
Results and Discussion

Experimental Results

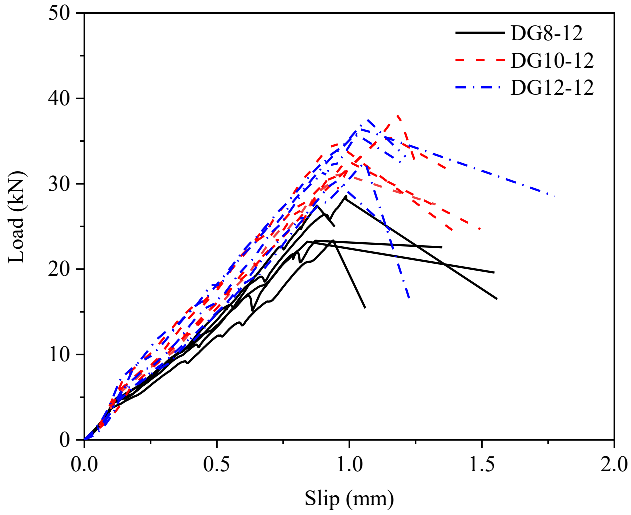
The maximum angle of eccentricity was within 0.2^o, which was obtained by the difference between the slips recorded by the two LVTDs divided by the distance between the two probes. It suggested that the load was applied under tension without eccentricities during the pull-out tests on the glued-in rods.

All the specimens were tested to failure within 1 min, and their short test duration is less than that recommended in the tensile tests on timber according to EN 408 (2010), where the maximum load shall be reached within 5 ± 2 min. It should be noted that the test duration could affect the pull-out capacity.

Table 3 summarizes the experimental results. Fig. 4 illustrates the load-slip curves from the pull-out tests on the densified wood (DW) dowels and threaded steel rods. The curves for the specimens with glued-in threaded steel rods showed fairly linear increases until the ultimate loads. The curves for the specimens with glued-in DW dowels firstly showed nonlinear increases up to the loads of about 5 kN, which could be related to the test set-ups, and then almost linear increases until the ultimate loads. As shown in Fig. 5, the failure modes were mostly pulling-out of the rod with more or less wooden plug. The splitting of the timber was only observed in one specimen with the glued-in threaded steel rod. There were no significant differences between the pull-out performances of the specimens with and without splitting, and thus the splitting could be regarded as a consequence of the internal shear failure of the wood (Steiger et al. 2006).



(a)



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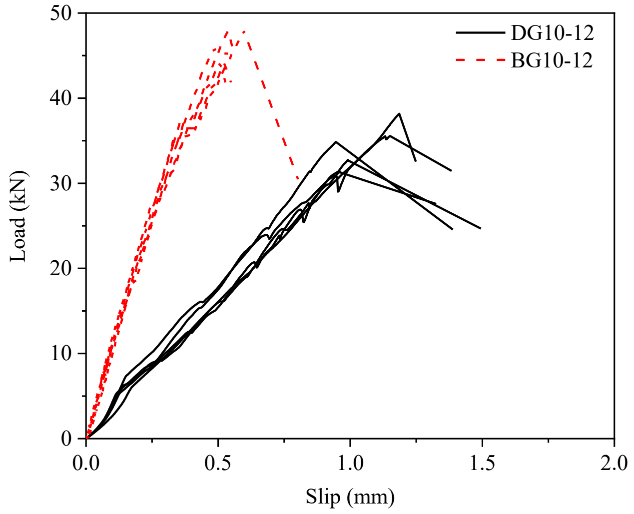
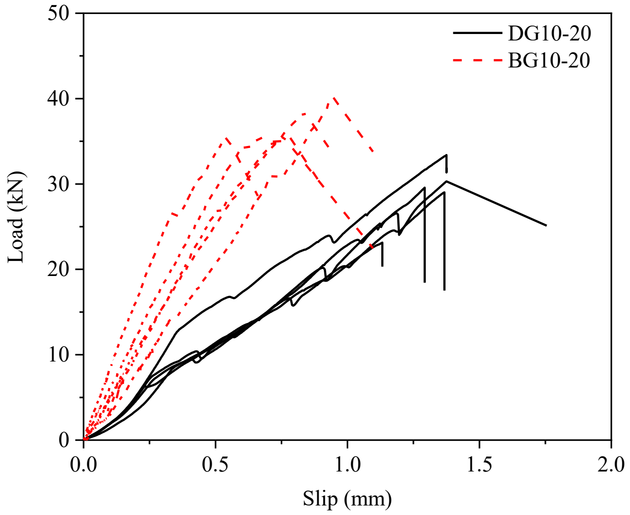


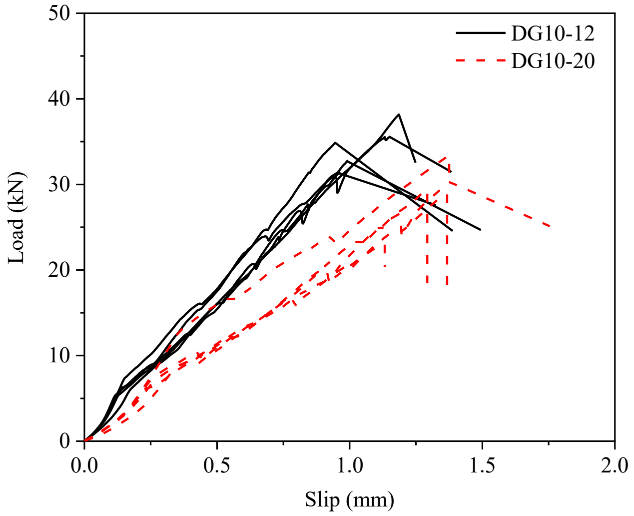
DG10-12
BG10-12
Load (kN)
Slip (mm)
0
10
20
30
40
50
0.0
0.5
1.0
1.5
2.0

(c)



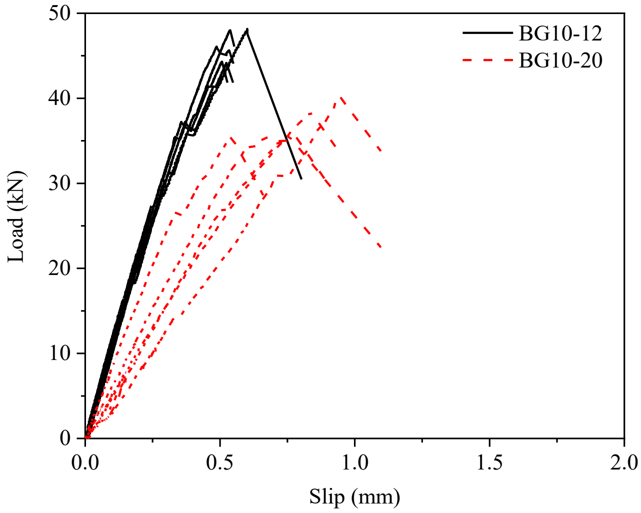
DG10-20
BG10-20
Load (kN)
Slip (mm)
0
10
20
30
40
50
0.0
0.5
1.0
1.5
2.0

(d)



DG10-12
DG10-20
Load (kN)
Slip (mm)
0
10
20
30
40
50
0.0
0.5
1.0
1.5
2.0

(e)

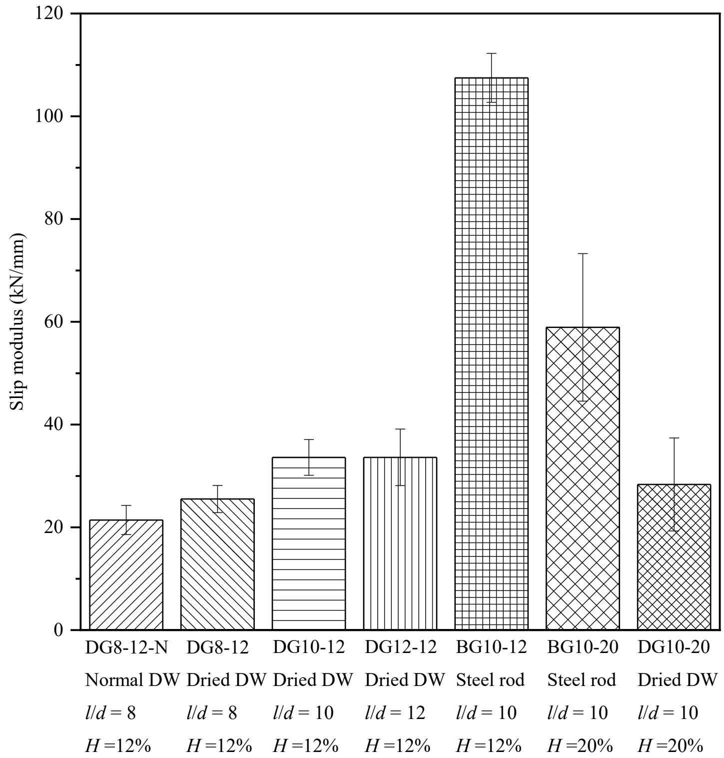


(f)

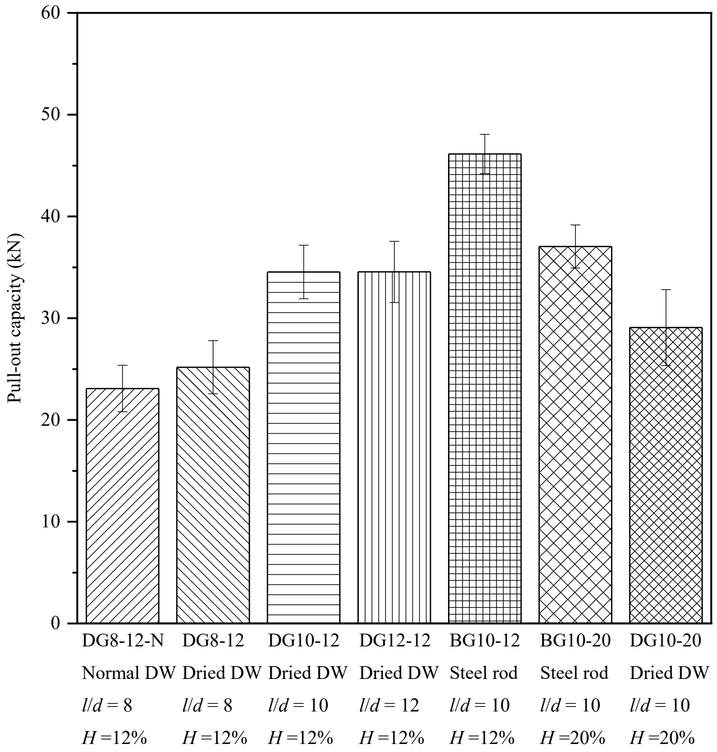
Fig. 4. Load-slip curves from the pull-out tests: (a) timber joint specimens with the glued-in DW dowels with an 8*d* anchorage length and two moisture contents for DW dowels; (b) timber joint specimens with the glued-in DW dowels with three anchorage lengths conditioned at a temperature of 20°C and relative humidity of 65%; (c) timber joint specimens with the glued-in DW dowels and threaded steel rods with a 10*d* anchorage length conditioned at a temperature of 20°C and relative humidity of 65%; (d) timber joint specimens with the glued-in DW dowels and threaded steel rods with a 10*d* anchorage length conditioned at a temperature of 20°C and relative humidity of 85%; (e) timber joint specimens with the glued-in DW dowels with a 10*d* anchorage length under two service environments; and (f) timber joint specimens with the glued-in threaded steel rods with a 10*d* anchorage length under two service environments.

(a) (b)

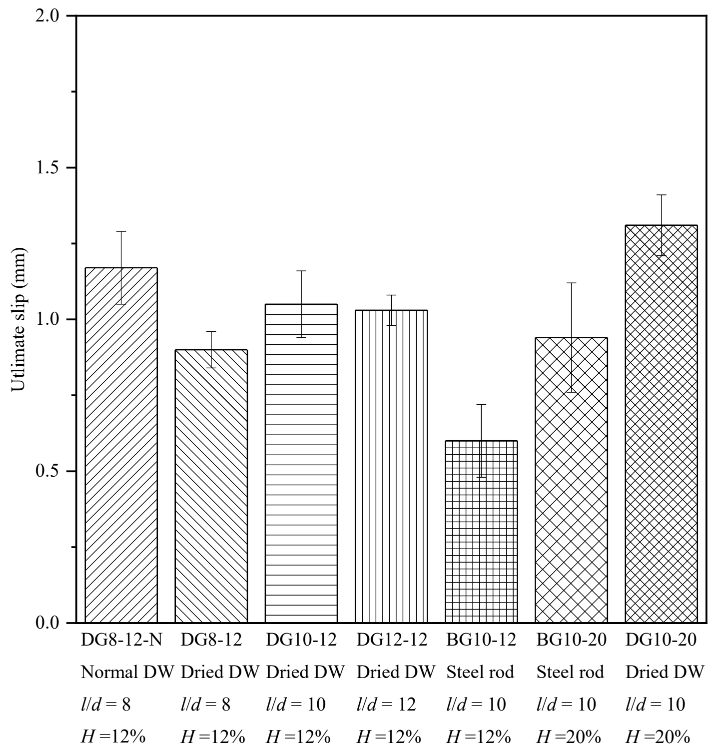
Fig. 5. Failure modes: (a) in timber joints with the glued-in DW dowels; and (b) in timber joints with the glued-in threaded steel rods.



(a)


Pull-out capacity (kN)
0
10
20
30
40
50
60
DG8-12-N
Normal DW
l/d = 8
H =12%
DG8-12
Dried DW
l/d = 8
H =12%
DG10-12
Dried DW
l/d = 10
H =12%
DG12-12
Dried DW
l/d = 12
H =12%
BG10-12
Steel rod
l/d = 10
H =12%
BG10-20
Steel rod
l/d = 10
H =20%
DG10-20
Dried DW
l/d = 10
H =20%

(b)


Utlimate slip (mm)
0.0
0.5
1.0
1.5
2.0
DG8-12-N
Normal DW
l/d = 8
H =12%
DG8-12
Dried DW
l/d = 8
H =12%
DG10-12
Dried DW
l/d = 10
H =12%
DG12-12
Dried DW
l/d = 12
H =12%
BG10-12
Steel rod
l/d = 10
H =12%
BG10-20
Steel rod
l/d = 10
H =20%
DG10-20
Dried DW
l/d = 10
H =20%

(c)

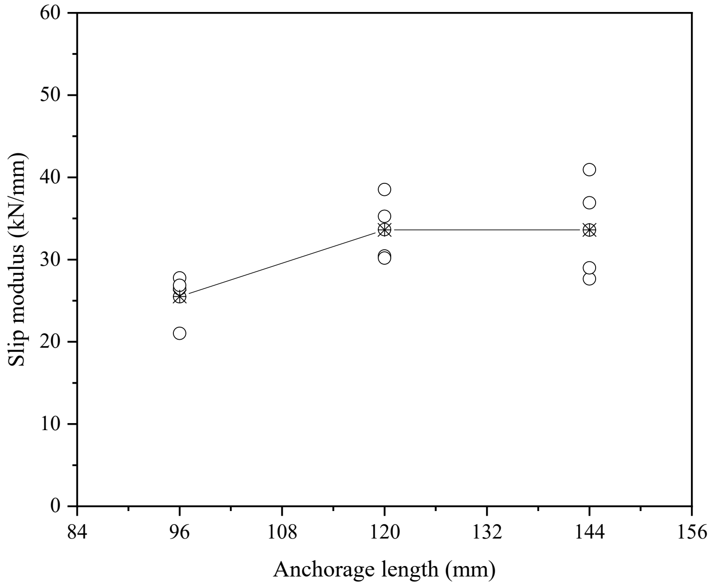
Fig. 6. Experimental results of individual test series: (a) slip modulus; (b) pull-out capacity; and (c) ultimate slip.

Influence of the Moisture Content of DW Dowels

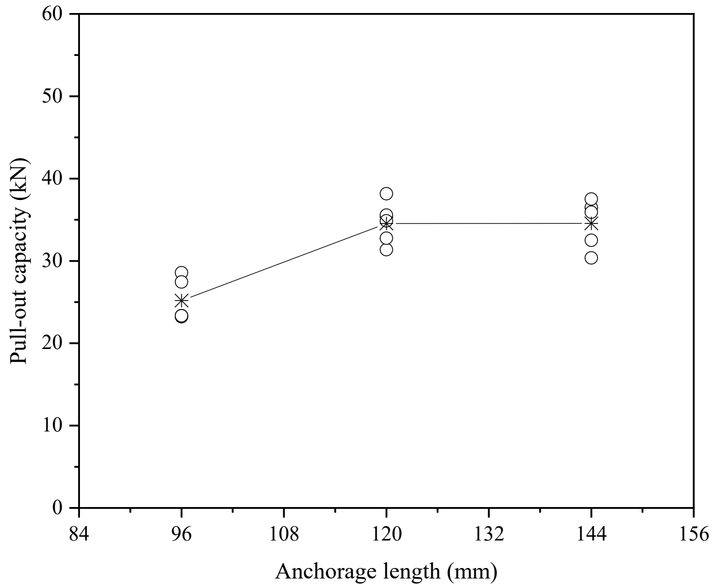
The dried DW dowels improved the slip modulus of the joints (K_s). However, the pull-out capacities (F_u) of the glued-in rods showed no significant differences for the specimens with the dried and normal DW dowels. Thus, the ultimate slips (V_u) of the joints with the dried DW dowels were less than those with the normal DW dowels.

Influence of the Anchorage Length

For the timber joints with the glued-in DW dowels conditioned under the ambient environment with a temperature of 20°C and relative humidity of 65%, the slip modulus (K_s) increased by 31.75% and the pull-out capacity (F_u) increased by 37.17% when the anchorage length increased from 8*d* to 10*d*, and they remained almost unchanged when the anchorage length increased from 10*d* to 12*d* as shown in Fig. 7. These results were the same as the observations in the previous study by Jung et al. (2010), where the ultimate load increased with the anchorage lengths at an early stage and became constant after a 10*d* anchorage length. Similarly, in the case of large anchorage length, the pull-out capacities of the glued-in steel rod joints were also not proportional to the anchorage length but levelled off (Otero-Chans et al. 2010; Yeboah et al. 2011).



(a)



(b)

Fig. 7. Influences of the anchorage length: (a) on the slip modulus; and (b) on the pull-out capacity.

Influence of the Rod Materials

After being conditioned at a temperature of 20°C and relative humidity of 65% and for a 10*d* anchorage length, the slip modulus (K_s) of the timber joints with the glued-in DW dowels was only 31.27% of that of the timber joints with the glued-in threaded steel rods, and the pull-out capacity (F_u) of the glued-in DW dowels was 74.86% of that of the glued-in threaded steel rods.

After being conditioned at a temperature of 20°C and relative humidity of 85% and for a 10*d* anchorage length, the slip modulus (K_s) of the timber joints with the glued-in DW dowels was 48.10% of that of the timber joints with the glued-in threaded steel rods, and the pull-out capacity (F_u) of the glued-in DW dowels was 78.49% of that of the glued-in threaded steel rods.

Influence of the Moisture Content

As shown in Table 3, the high moisture content caused greater scatters in terms of the slip modulus (K_s). For the timber joints with the glued-in DW dowels with a 10*d* anchorage length, with the increasing moisture content, the slip modulus (K_s) showed no significant differences, the pull-out capacity (F_u) decreased by 15.81%, and the corresponding ultimate slip (V_u) significantly increased.

For the timber joints with the glued-in threaded steel rods, with the increasing moisture content, the slip modulus (K_s) decreased by 45.18%, the pull-out capacity (F_u) decreased by 19.70% and the corresponding ultimate slip (V_u) significantly increased. This suggests that the impact of service environments would be greater for the glued-in steel rod joints than the glued-in DW dowel joints.

For a 10*d* anchorage length, though the slip modulus (K_s) of the timber joints with the glued-in threaded steel rods conditioned at a temperature of 20°C and relative humidity of 85% was still higher than of the timber joints with the glued-in DW dowels conditioned at a temperature of 20°C and relative humidity of 65%, their pull-out capacities had no significant differences.

Conclusions

This study compared the pull-out performances of the densified wood (DW) dowels and threaded steel rods glued into the glulam parallel to the grain under two ambient environments with a temperature of 20°C and relative humidity of 65% corresponding to service class 1 and with relative humidity of 85% corresponding to service class 2 according to Eurocode 5.

As the dried DW dowels were glued into the timber, the slip modulus was enhanced, but the pull-out capacities showed no significant differences compared with the normal DW dowels.

For the timber joints with the glued-in DW dowels, their slip modulus increased by 31.75% and the pull-out capacity increased by 37.17% with the increasing anchorage length from 8*d* to 10*d*, and then they became constant after the 10*d* anchorage length.

After being conditioned at a temperature of 20°C and relative humidity of 65% and for a 10*d* anchorage length, the pull-out capacity of the glued-in DW dowels was 74.86% of that of the glued-in threaded steel rods. The pull-out capacity significantly decreased with the increasing moisture content. The impact of service environments would be greater for the timber joints with glued-in steel rods than the timber joints with glued-in DW dowels.

The pull-out capacity of the glued-in threaded steel rods conditioned at a temperature of 20°C and relative humidity of 85% had no significant differences from that of the glued-in DW dowels conditioned at a temperature of 20°C and relative humidity of 65%.

It should be noted that the timber joints with glued-in DW dowels and threaded steel rods were tested under different set-up methods in this study, and the test set-up methods could affect the test results.

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Data Availability

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

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