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Experimental evaluation of dowel-type timber joints with wooden dowels

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Dowel-type timber joints made of wood are of particular interest for interventions on built heritage because such heritage buildings often involve timber structures. Wooden dowels offer a lower cost when compared with other connectors and conform to the tendency for using wood-based solutions to retrofit timber structures. However, there is a significant lack of information regarding the modelling of these wooden connectors' responses, in terms of analytical expressions as numerical models. Therefore, this paper presents the results of an extensive experimental campaign of timber-to-timber joints using wooden dowels. Two wood species were considered: Chestnut as a hardwood and Spruce as a softwood. The wooden dowels were always made of massaranduba, a Brazilian hardwood. The aim of the experimental campaign was to obtain and analyse the response of this type of connection, and then to compare it with the load-carrying capacity accessed through the available analytical expressions to verify its accuracy. The test results highlighted the advantages of using wooden dowels in timber joints. Moreover, it became clear that further analysis and research studies are needed to suggest new expressions that are in accordance with the behaviour of the connection.

Notation

$D_{\max}$	deformation corresponding to maximum load, $F_{\max}$
d	fastener diameter (mm)
$F_{ax,Rk}$	characteristic axial withdrawal capacity of the fastener
F_b	bending strength of dowel
F_{cvf}	embedment yield stress in dowel
F_{ecp}	embedment strength
$F_{e,exp}$	embedment strength in joint components (N/mm^2)
$F_{\max}$	maximum load (N)
$F_{v,Rk}$	characteristic load capacity per shear plane per fastener (kN)
F_y	yield force
$f_{c,0}$	compression parallel to the grain (MPa)
f_h	embedding strength (N/mm^2)
$f_{h,k}$	characteristic embedment strength (kN/mm)
$f_{h,0,k}$	embedding strength according to Equation 5
$f_{m,k}$	bending strength of dowel
$f_{t,0}$	tension parallel to the grain (MPa)
f_v	shear strength (MPa)
$M_{\max}$	bending moment resulting from maximum load, $F_{\max}$
M_p	plastic capacity of dowel
$M_{u,k}$	bending moment of dowel
M_y	yield value of bending moment
$M_{y,k}$	characteristic fastener yield moment
$P_{\max,exp}$	experimental maximum force (N)
R_k	shear load-carrying capacity
s_B	bending strength of the wood species
t	thickness (mm)
t_1, t_2	timber or board thickness or penetration depth (mm)
W	moisture content
α_F	amplification coefficient
β	ratio between embedding wood strength of the joint components 1 and 2
δ	reduction coefficient
ρ	density of wood (kg/m^3)
ρ_{Holz}	density of dowel (kg/m^3)
ρ_{st}	wood density

1. Introduction

The restoration and conservation of old historical timber buildings has been an area of interest because there is a need to preserve structures that form part of the architectural heritage. This is done by replacing deteriorated timber elements or strengthening them to support the structure. The restoration process of timber buildings presents difficulties to both researchers and designers. This is mainly because the replaced or strengthened elements of a structure must fulfil both the resistant demand and its restoration function. Interest in wooden connections has been increasing because historical restorations have to be accurate and to follow as much as possible the original design, materials and building techniques.

Researchers such as Bertolini (Bertolini-Cestari *et al.*, 2016; Bertolini-Cestari, 2019; Cestari *et al.*, 2011; Spano *et al.*, 2015) have detailed the restorations of some historical buildings, such as the great timber roof of Porta Nuova railway station in Turin (Italy), the timber roof structures of the Cathedral of Vercelli and the roof of Valentino Castle in Turin (Italy) with their processes, methods and innovative technologies. They concluded that a proper analysis on timber elements made the restoration easier and more accurate.

However, there is a lack of information and guidelines regarding the design of timber-to-timber joints using wooden dowels; most standards refer to dowel-type connections that use steel dowels. This gap in the knowledge is a major concern, as this type of connection is regarded as one of the most fragile and important parts of a timber structure (Santos *et al*., 2009). Moreover, historical buildings commonly have this all-wooden type of connection and the available numerical expressions to determine the load-carrying capacity present a considerable discrepancy with experimental results.

Dowel-type connections are widely employed in construction because they are easy to use and relatively cheap. In terms of design, it is essential to understand their mechanical properties and the factors that affect their behaviour. The mechanical properties are dependent on parameters such as the wood species, dimensions, diameter of the fastener and loading configuration, together with external factors like climatic conditions (temperature and humidity), moisture content, biological factors (insects, moulds), age of wood and state of the connections (if they have been affected by time, insect damage etc.).

A bibliographic review was conducted in an attempt to better understand and describe the performance of wooden connectors and to assess the efficiency of different standard guidelines in order to find more adequate solutions for the proposed models. For this purpose, the behaviour of these connections and the parameters involved have been studied.

Rohana *et al*. (2010) reported the performance of mortise and tenon connections fastened with wooden and steel dowels. The joints connected by steel dowels proved to have higher resistance than those with wooden dowels for both bending and shear tests.

Blaß and Laskewitz (2003) used wooden dowels to transfer the load between timber elements in the joint structure, instead of metallic ones. They developed a testing model based on theoretical considerations and analysed the properties of the connections and the forces that intervene in the deformation process. Moreover, they proposed an investigation of which factors influence the connections' behaviour the most.

Milch *et al*. (2017) presented theoretical and experimental approaches to determine the load-carrying capacity for bending and shear deformation of wooden dowels according to design, as proposed by Fukuyama *et al*. (2008). The design method is based on the European yield model (EYM) and aims to predict the load-carrying capacity of single shear dowel-type joints, per shear plane, loaded laterally to its axis. The authors concluded that the mathematical design of wooden dowels that was introduced seems to be a suitable tool for predicting the properties of all-wooden joints with respect to safety level.

A recent study, conducted by El-Houjeyri *et al*. (2019), also supports the use of wooden dowels instead of metal fasteners. In their study, they attempt to fulfil a gap of knowledge regarding this type of connections because, according to them, even though wooden dowels have been used in the past, the information on their mechanical behaviour and performance is still 'limited'. Therefore, they conducted tests on compressed wooden dowels from joints under double-shear and achieved satisfying results in terms of their mechanical performance.

In this context, the aim of the experimental campaign presented in the current paper is to contribute to a better understanding of the mechanical behaviour of timber-to-timber connections using wooden dowels when exposed to different environmental conditions. For this purpose, several tests have been conducted on wooden connections of two different species: chestnut (*Castanea sativa*) and spruce (*Picea abies*), connected by a dowel of massaranduba (*Manilkara* spp).

The experimental campaign covers the dowel and the connection behaviour. The massaranduba dowel was tested to assess its bending yield strength. With regard to the joints, embedding tests were performed on connections made of chestnut, spruce and cross-laminated timber (CLT, made of spruce) for a moisture content of 12%, and double-shear tests were made on connections of chestnut and spruce for three levels of moisture content at 8, 12 and 16%, achieved in a climatic chamber. The experimental results obtained were compared to the values given by analytical expressions available in the relevant bibliography and international standards.

2. Experimental campaign

The experimental campaign was conducted at the University of Minho, in Portugal, and was divided into embedment strength and double-shear tests performed on connections with wooden dowels. The latter were made with various moisture contents: 12%, which is the reference value adopted by standards, 16% and 8%. These values were modified in a climatic chamber. In the following sections, the different steps of the experimental campaign are presented and discussed.

2.1 Bending yield strength of wooden dowels

This experiment is regarding the bending capacity of the massaranduba (*Manilkara spp*) dowels. The test is based on EN 409:2009 (CEN, 2009) and shows the mechanical behaviour of fasteners that are subject to bending. Although this standard covers dowel-type fasteners manufactured from steel, the authors decided to base the experiments on it because of the absence of a pertinent guideline regarding wooden dowels. Moreover, in a further section, proposed expressions by different researchers demand the assessment of wooden dowels under bending. Massaranduba (*Manilkara spp*) is a Brazilian wood – hard, heavy and with a high degree of resistance to insects and fungal attacks. In accordance with NBR 7190:1997 (NBR, 1997), this Brazilian hardwood presents mean values, for a moisture content of 12%, for the compression parallel to the grain ($f_{c,0}$) of 82.9 MPa, a tension parallel to the grain ($f_{t,0}$) equal to 138.5 MPa and a shear strength (f_v) of 14.9 MPa.

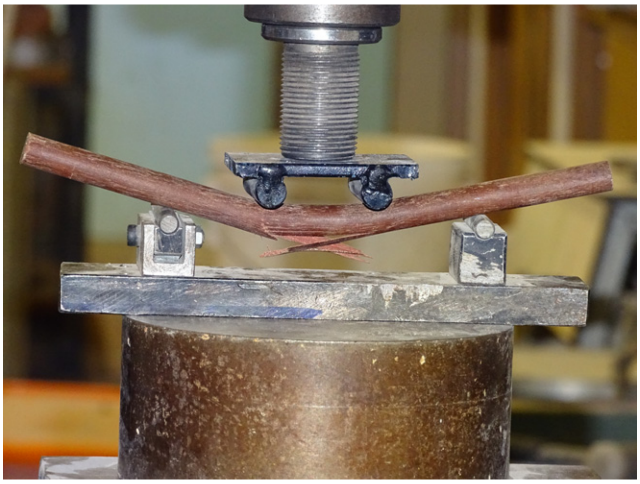


Figure 1. Bending of a wooden dowel following the set-up proposed by CEN (2009)

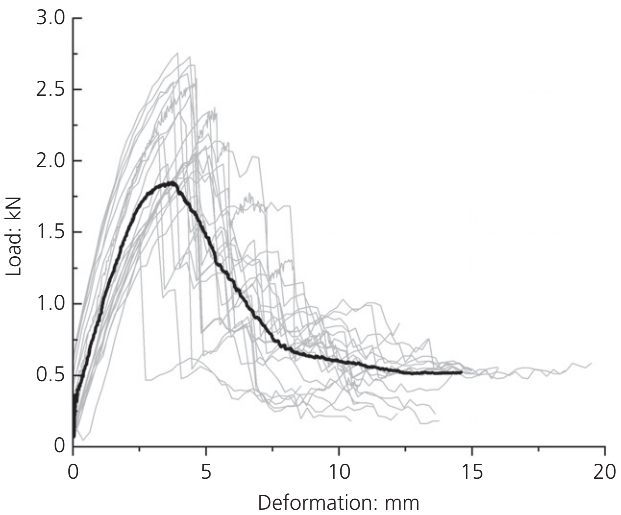


Figure 2. Experimental load–deformation obtained from the bending tests performed on the massaranduba 12 mm dowels

Twenty massaranduba dowels with a diameter of 12 mm and length of 230 mm were bent until rupture, and the respective maximum bending, deformation and yield moment were registered. Figure 1 shows the test set-up.

Figure 2 presents the series of results from the bending tests made on wooden dowels of massaranduba. The series follow the same pattern, with a continued growth until 2–4 mm of deformation until the rupture, where the force decreases until the dowel cannot be used any longer (it breaks or the damage is too great for the dowel to be used in a connection).

Table 1 summarises the mean values collected from the bending tests performed on the wooden dowels following EN 409:2009 (CEN, 2009). F_{max} consists of the maximum mean force supported by the dowels with D_{max} being the corresponding deformation and M_{max} the resulting bending moment (assuming a lever arm of 45 mm). The yield force F_y was determined by fitting a line to the elastic slip average curve and finding the value where the R^2 falls below 95% as the end of the elastic limit. M_y is the corresponding yield value of the bending moment. For control purposes, the density (ρ) of all the wooden dowels in the tests was measured.

2.2 Embedment strength tests

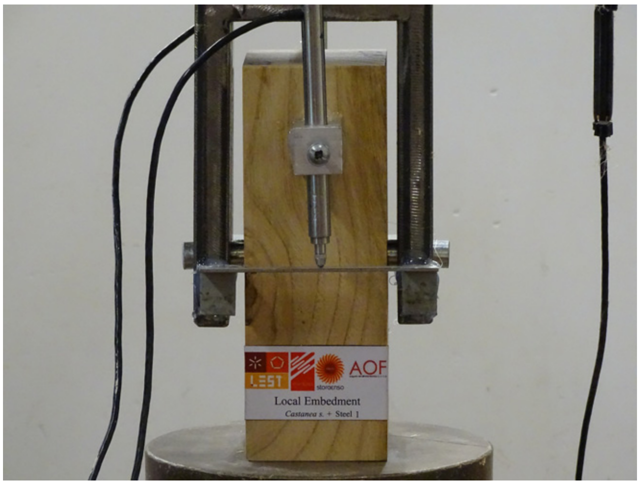
The test procedure follows the principles described in EN 383:2007 (CEN, 2007), where the test piece is placed symmetrically in the metallic test apparatus so that the load can be applied on its axis. Two displacement transducers (LVDTs) are placed on opposite edges (Figure 3). For each series of tests, the first experiment must be monotonic in order to obtain the maximum estimated force, with a constant rate of 0.02 mm/s and a displacement control. The loading procedure supposes that the load increases up to 0.4 $F_{max,est}$ and is maintained for 30 s. Then the load is reduced to 0.1 $F_{max,est}$ and maintained for another 30 s. The test stops when the deformation reaches 15 mm or the dowel breaks completely. For the embedment tests, three types of wooden samples (168 × 60 × 70 mm) were used: chestnut (*C. sativa*), spruce (*P. abies*) and CLT made of spruce, with two different types of dowels: wood (massaranduba) and steel, both with a diameter of 12 mm. Seventy-two tests were performed, divided into 12 tests for each series.

The embedment strength is calculated as follows: $f_h = F_{max}/dt$, where f_h is the embedding strength (N/mm^2), F_{max} is the maximum load (N), d is the fastener diameter (mm) and t is the thickness (mm). Table 2 summarises the results obtained for spruce (Figure 3(a)) and chestnut (Figure 3(b)); as expected, the performance of the steel dowels is superior, the

Table 1. Yield values of the tests performed on the dowels of massaranduba

ρ: kg/m^3	F_{max} : N	M_{max}: kNmm	CoV: %	D_{max}: mm	CoV: %	F_y: N	M_y: Nmm
1127	2209	49695	16.50	13.28	20.82	1780	40050

(a)



(b)

Figure 3. Set-up according to EN 383:2007 (CEN, 2007) adopted for the embedding strength considering (a) wooden dowels and (b) steel dowels

maximum load obtained (41.44 kN for chestnut, 22.51 kN for spruce and 25.20 kN for CLT) being higher than that for the wooden dowels (9.15 kN for chestnut, 8.16 kN for spruce and 8.61 kN for CLT).

Figure 4 provides the respective load–displacement curves, where it can be observed that the deformation capacity is higher for samples with wooden dowels (for chestnut 15.52 mm) than for steel ones (for chestnut 9.98 mm). In contrast, for the CLT elements, the steel and the wooden dowels have a similar deformation capacity; they can reach up to 15.5 mm. In general, for the steel dowels, the failure is sudden, with a fragile nature, while in the case of the wooden dowels, the failure is preceded by large deformations and, therefore, with an improved ductility.

In Figure 5, a direct comparison is presented between the wooden and steel dowels, where the dotted curves represent the connections with steel dowels and the solid ones represent the connections with wooden dowels. It can clearly be seen, for both spruce and chestnut (values up to 8 mm), that the steel dowel joints have higher resistance in terms of the load applied (values above 20 kN), but smaller resistance over time in terms of deformation. The higher deformation values for the wooden dowels' joints show their qualities and resistance over time. Moreover, wooden dowels are advantageous because, after the dowel collapses, it still presents a decreasing linear resistance, whereas the metallic ones present a sudden failure and cannot be used after the rupture.

For the CLT samples, the curves are in accord with each other in terms of deformation; however for resistance, the value is higher for the steel dowel.

2.3 Load-carrying capacity of wooden dowel joints

Load-carrying capacity tests following EN 26891:1991 (CEN, 1991) were performed (see Figure 6). Again, three species of wooden elements (168 × 90 × 70 and 168 × 60 × 70 mm) were considered: spruce, chestnut and CLT made of spruce. One series was tested at a reference moisture content value of 12% and then for the others at 8% and 16% (for spruce and chestnut).

The test procedure was similar to the one from the embedment tests and is in accordance with EN 26891:1991 (CEN, 1991). Initially, a monotonic test was conducted to find the maximum force reached before the connection broke. This value is used later, in the next experiment, which starts with a force control of 0.022 kN/s until 40% of the estimated force, then remains at that value for 30 s. Then the load decreases with 10% of the estimated force at the same rate and remains

Table 2. Mean values of the tests results obtained for the 72 embedment tests

Series	Dowels	F_{mean}: kN	f_h: N/mm^2	CoV: %	Deformation: mm	CoV: %
Spruce	Wood	8.2	11.3	13.9	12.1	20.7
	Steel	22.5	31.3	17.2	5.9	8.5
Chestnut	Wood	9.2	12.7	13.6	15.1	7.4
	Steel	41.4	57.6	8.9	9,9	28.8
CLT	Wood	8.6	11.9	14.6	15.5	8.5
	Steel	25.2	35.0	9.4	15.8	9.2

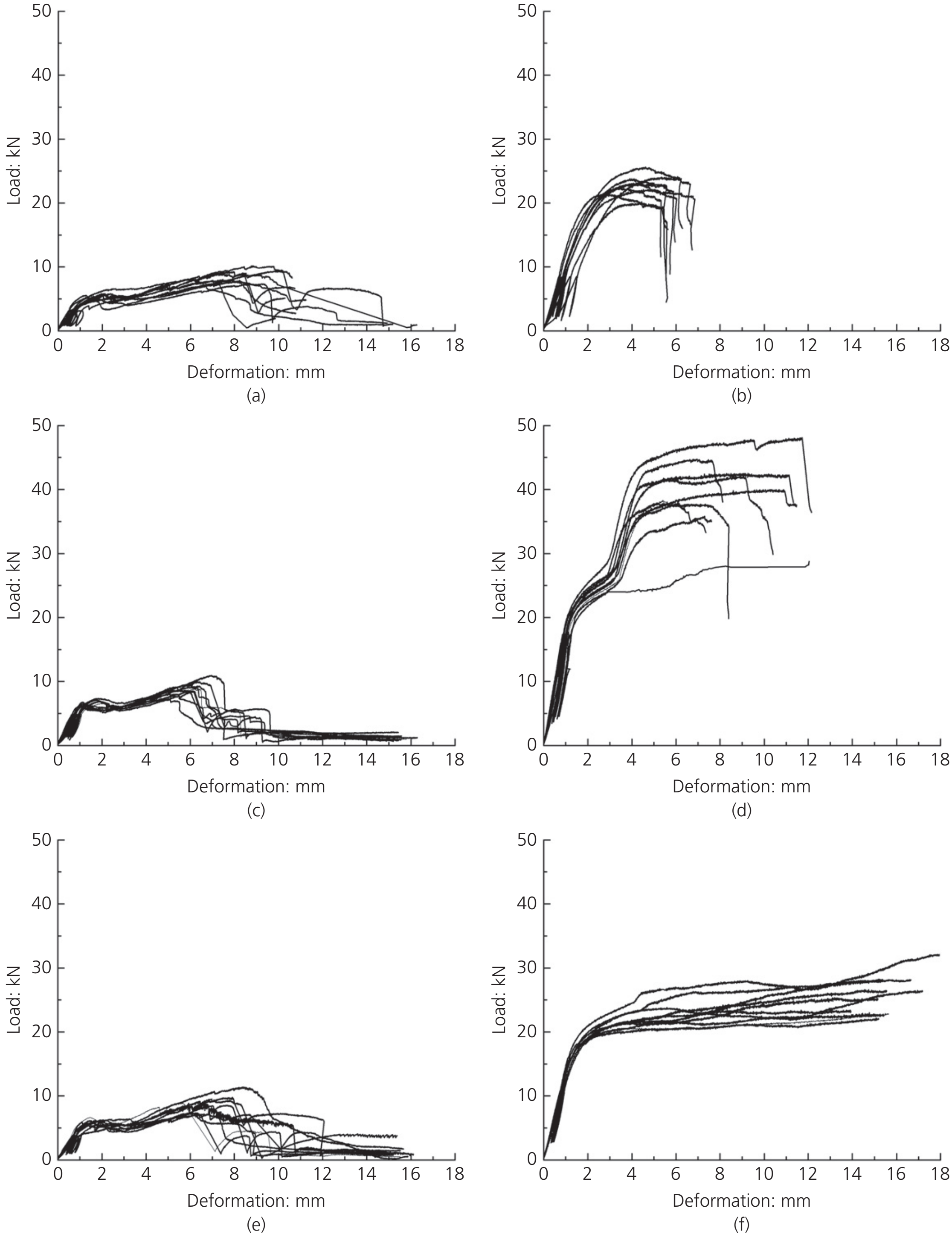


Figure 4. Experimental load–displacement curves obtained for embedment tests performed on: (a) spruce with wooden dowels; (b) spruce with steel dowels; (c) chestnut with wooden dowels; (d) chestnut with steel dowels; (e) CLT with wooden dowels; (f) CLT with steel dowels

there for 30 more seconds. It is then applied at a maximum rate until 15 mm of displacement is reached or the dowel breaks completely.

Figure 4 presents the configuration of the double-shear connection experiments built by three pieces of wood, where the species are linked together by a wooden dowel of

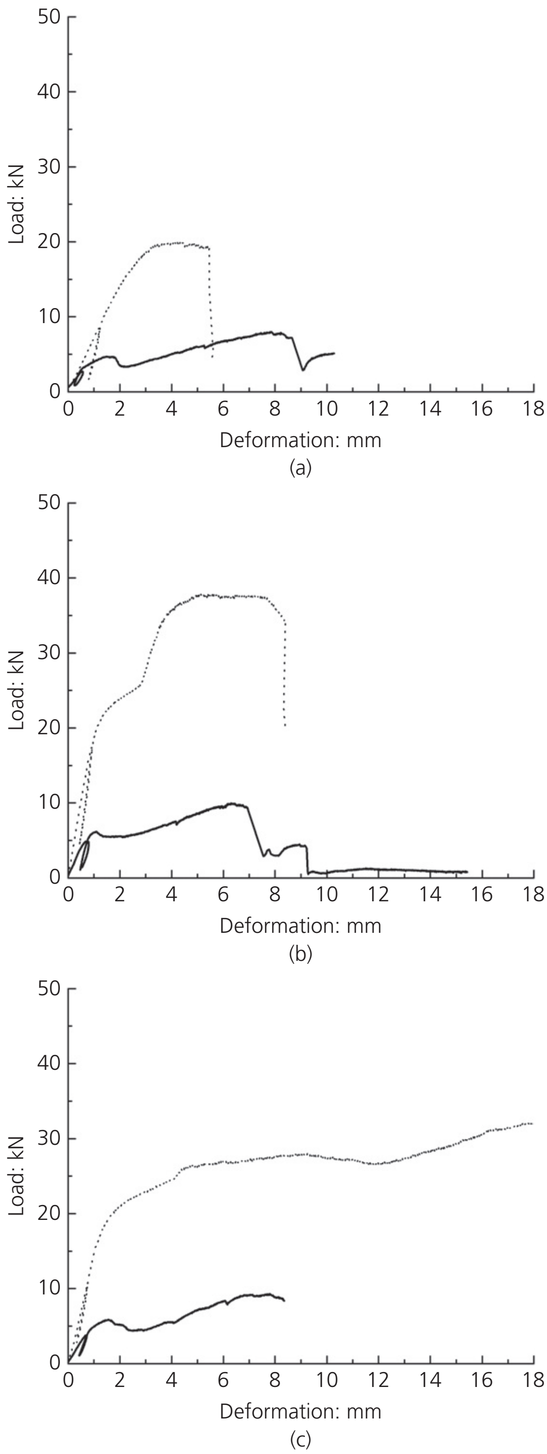


Figure 5. Comparison between the mean experimental load–deformation curves for (a) spruce, (b) chestnut and (c) CLT elements with wooden and steel dowels (dotted line, steel dowels; solid line, wooden dowels)

massaranduba. The steel block on which the force is applied is fixed on the centre piece; three LVDTs are used to measure the data from the loading machine.

Figure 7 presents the series for the experimental load–displacement curves obtained during the tests performed on the dowel-type connections with spruce and chestnut. For these experiments, three moisture contents have been considered: 8, 12 and 16%. The values of the loads for each series and their displacement can be seen on the graphs. Results show that the series of chestnut samples are more resistant over time and by load (up to 18 kN) compared with the spruce samples (up to 12 kN). In terms of displacement, the values are similar for both species (they reach up to 15 mm). With respect to failure, the spruce samples presented a line that was almost linear after the rupture point for 12 and 16% moisture content, while the chestnut samples present a sudden rupture for 8 and 12% moisture content.

These differences between the two species are related to their mechanical properties; hardwood species (chestnut) are more resistant than softwood species (spruce).

For the CLT samples, tests were conducted only for 12% moisture content. Because these samples are made of spruce, they can be compared with the spruce samples at 12% moisture content. Figure 8 displays higher resistance in terms of load (up to 12 kN) and displacement (up to 18 mm) for CLT. Furthermore, the failure is brittle, even though the connection still functions, whereas for spruce, the connection breaks gradually.

In more detail, Table 3 presents the mean values obtained from the double-shear tests for the three moisture contents considered in this study. It can be pointed out that the maximum force for chestnut is found when the moisture content is 16% (15.02 kN), but does not differ much from that at 12% (14.72 kN). For spruce, the maximum force is found for 12% moisture content (11.39 kN). Regarding the displacement, the maximum value for the two wooden species is seen for 12% moisture content: chestnut has a displacement of 17.45 mm and spruce of 15.81 mm.

When comparing CLT and spruce for 12% moisture content, it can be noted that the mean value of the load applied and the displacement on the connection is slightly higher for spruce, which is 14.72 kN and 17.46 mm against 12.60 kN and 16.96 mm for CLT.

For direct comparison between the performance of the wood species adopted in this study, Figure 9 presents the mean experimental load–displacement curve at each moisture content considered. Spruce samples have the same pattern of load distribution. However, for the moisture content of 16%, the load-carrying capacity is higher, followed by the result for 8% moisture content in terms of load, but by the the result for moisture content of 12% in terms of load and displacement.

For the chestnut samples, the highest values of the load are for 12% moisture content, but with lower values for the

(a) (b)

(c)

Figure 6. Set-up of the double-shear tests performed to evaluate the performance of the wooden dowels: (a) spruce; (b) chestnut and (c) CLT made of spruce

displacement. This is followed by the series with 8 and 16% moisture content.

3. Discussion

3.1 Embedment strength

Eurocode 5 (EN 1995-1-1 (CEN (2004)) highlights that the embedding strength of wood f_h depends on its density, $f_{h,0} = 0.082(1 - 0.01d)\rho$ where $f_{h,0}$ is the embedding strength in the wood grain direction (N/mm^2), d represents the diameter of the dowel (mm) and ρdenotes the density of wood (kg/m^3). On the other hand, American standard NDS (2001) proposes a different dependency on density, $f_{h,0} = 0.07725\,\rho$.

Glišović *et al.* (2012) considered empirical equations from national standards and from research studies based on embedding strength that depends on wood density, diameter of the dowel and orientation of the load on the wood grain fibres.

One of the predictions adopted for the embedment strength is made in the research of Köhler and Leijten (2004), who evaluated embedment tests in a probabilistic way.

This study suggests the following expressions to quantify the embedding strength:

1. $$f_{h,0} = 0.097\,\rho^{1.07}d^{-0.25} \quad \text{softwood}$$
$$f_{h,0} = 0.087\,\rho^{1.09}d^{-0.25} \quad \text{hardwood}$$

A former study made by Blass *et al.* (1999) proposes an expression where the embedding strength is directly influenced by the density of the wooden dowel.

2. $$f_{h,0} = \rho_{st}\rho_{holtz}10^{-4} \times 1.222(1 - 0.011d)$$

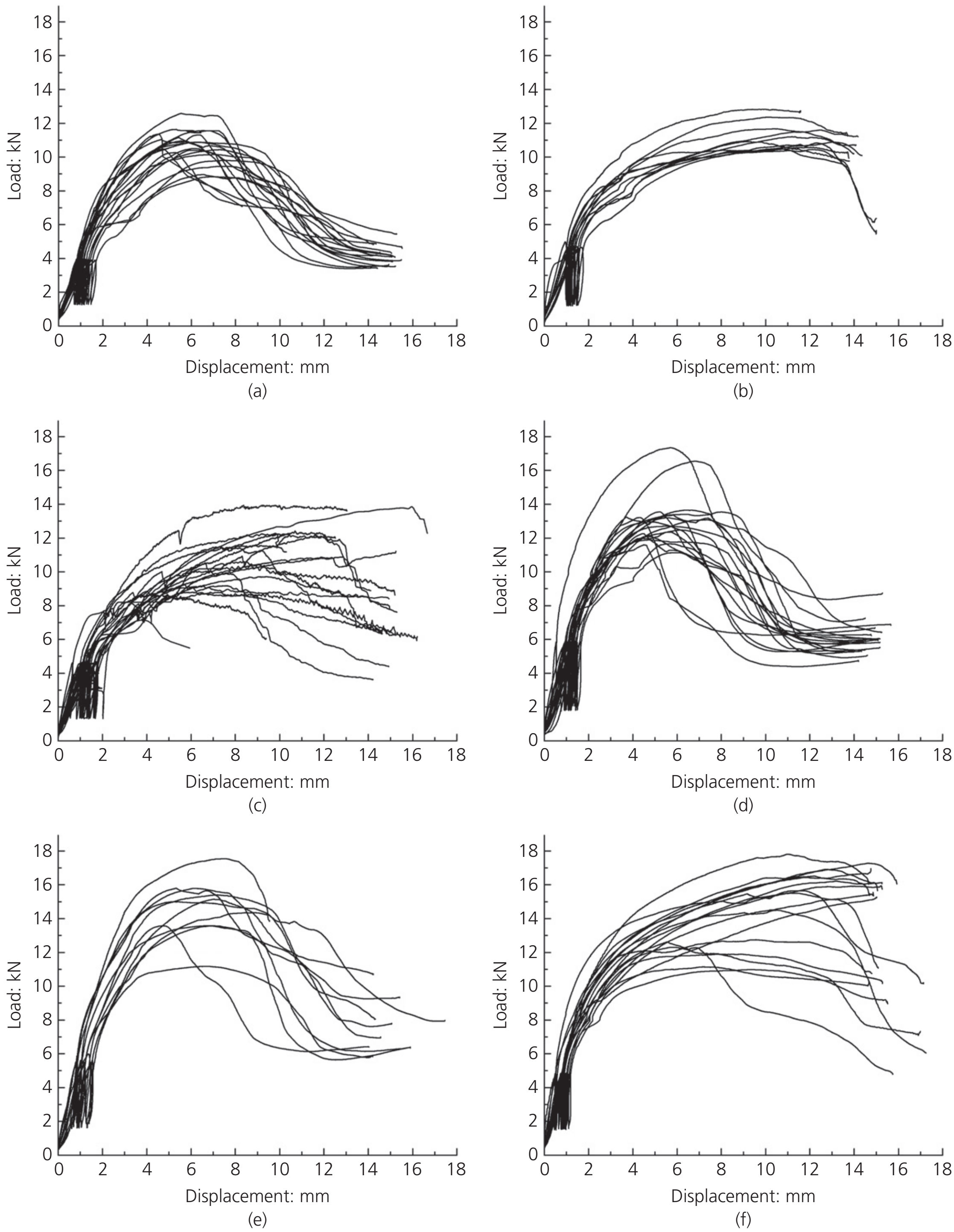


Figure 7. Experimental load–displacement curves of spruce with moisture content of: (a) 8%; (b) 12%; (c) 16%; and chestnut with moisture content of: (d) 8%; (e) 12%; (f) 16%

where ρ_{st} represents the wood density; ρ_{Holz} represents the density of the dowel (kg/m^3); and d denotes the diameter of the dowel (mm).

In Table 4, the experimental results are compared with the predicted ones resulting from the expressions above. The experimental values for the connections with steel dowels and

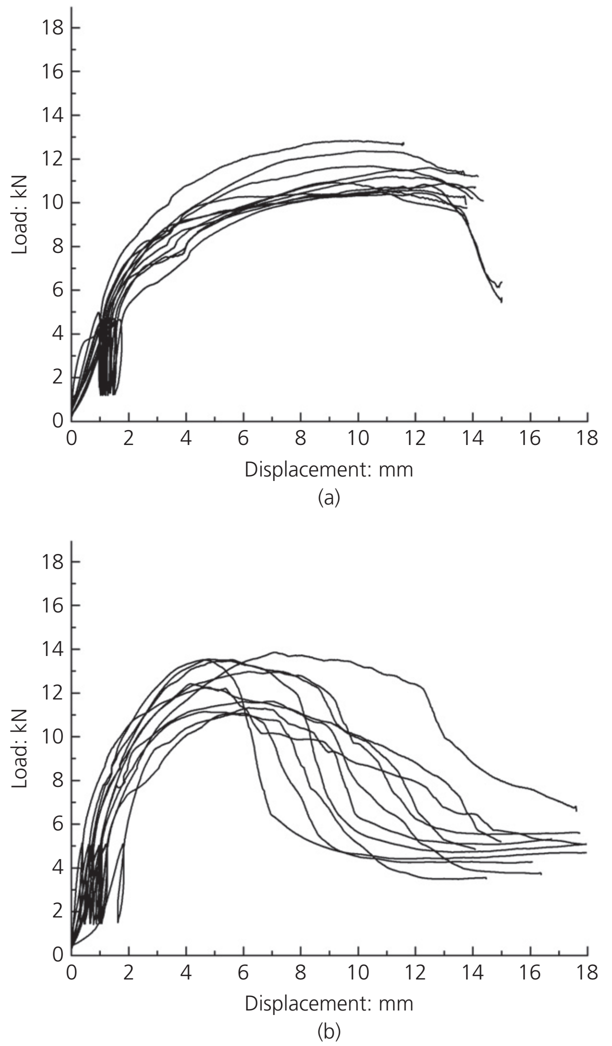


Figure 8. Mean experimental load–displacement curves obtained for the specimens made of (a) spruce and (b) CLT for 12% moisture content

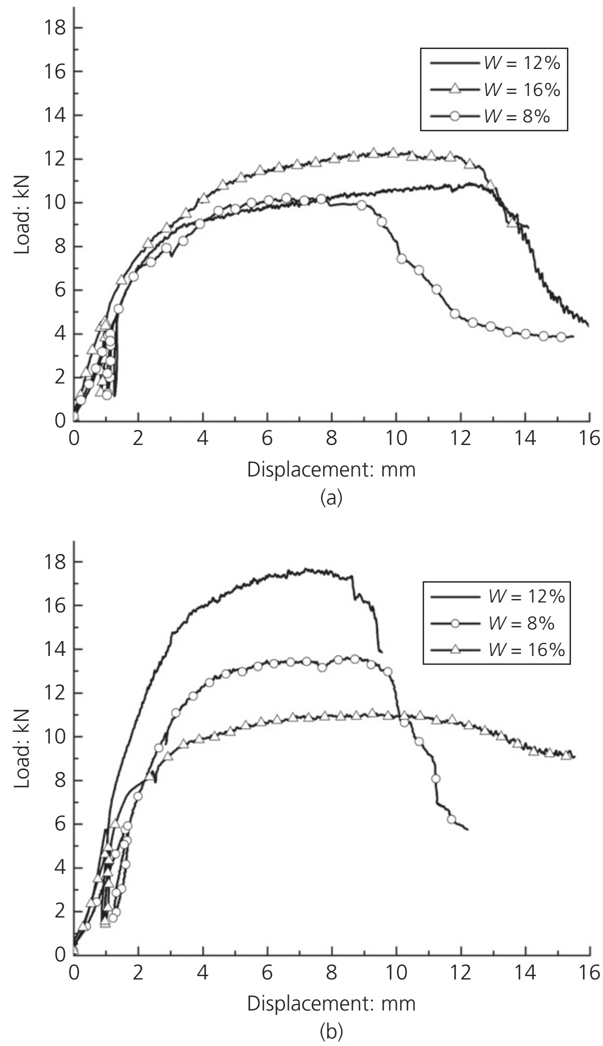


Figure 9. Mean experimental load–displacement curves obtained for (a) spruce and (b) chestnut and considering the three different moisture contents (8, 12 and 16%)

Table 3. Double-shear test mean results for different moisture contents of chestnut, spruce and CLT

Series			Displacement: mm	
Species	*W*: %	$F_{v,R}$: kN	Mean	CoV: %
Chestnut	8	13.4	14.7	2.9
	12	14.7	17.5	10.6
	16	15.0	15.5	5.5
Spruce	8	10.8	14.3	12.4
	12	11.4	14.3	9.7
	16	10.9	14.0	14.4
CLT	12	12.6	16.9	12.4

wooden dowels are compared with the values from the numerical expressions. For the theoretical results, and in accordance with the bibliography, the following density values have been assumed: 380 kg/m^3, 700 kg/m^3 and 420 kg/m^3 for spruce, chestnut and CLT, respectively. A density value of 1127 kg/m^3 was measured for the massaranduba wooden dowels used in the experimental campaign.

From Table 4, the theoretical expressions are not applicable in the case of wooden dowels. All the predictions are considerably higher than the test results. However, this does not occur in the case of steel dowels. For instance, the Eurocode 5 (EN 1995-1-1 (CEN (2004)) values are close to the test results obtained, and always on the safe side (lower).

3.2 Double-shear tests

The current version of Eurocode 5 (CEN, 2004) does not mention wooden dowels. The EYM is followed for dowel-type joints and only connections with metal fasteners are addressed.

Table 4. Comparison between the tests results of the embedding strength, $f_{h,0}$ (N/mm^2), with theoretical calculations suggested by standards and research studies

Wood species	Experimental campaign		Eurocode 5	Blass *et al.* (1999)	NDS	Köhler and Leijten (2004)
	Wooden	Steel				
Spruce	11.3	31.3	27.4	43.5	29.4	30.0
Chestnut	12.7	57.5	50.5	80.2	54.0	59.0
CLT	11.9	35.0	30.3	48.1	32.4	33.4

Table 5. Comparison between the test results and the theoretical ones for the load-carrying capacity of the dowel-type joints with wooden dowels for joints specimens with w = 12%

Series	Tests		Eurocode 5	Blass *et al.* (1999)	Fukuyama *et al.* (2008)
	F_{max}: kN	CoV: %	$F_{v,Rk}$: kN	R_k: kN	$P_{y,EYM,cal}$: kN
Chestnut (700 kg/m^3)	14.7	11.4	8.04 (13.94)	6.74 (15.51)	15.82
Spruce (380 kg/m^3)	11.4	6.6	7.46 (13.32)	6.26 (12.91)	15.82
CLT (420 kg/m^3)	12.6	8.1	7.78 (11.68)	6.53 (11.32)	15.82

In accordance with Eurocode 5, the load-carrying capacity of a connection in double shear, per fastener and per shear plane, can be calculated by:

$$3.\quad F_{v,Rk} = \min\begin{cases} f_{h,1,k}\, t_1\, d \\ 1.05\,\dfrac{f_{h,1,k}\, t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\dfrac{4\beta(2+\beta)M_{y,Rk}}{f_{h,1,k} d\, t_1^2}}-\beta\right]+\dfrac{F_{ax,Rk}}{4} \\ 1.15\sqrt{\dfrac{2\beta}{1+\beta}}\sqrt{2M_{y,Rk} f_{h,1,k} d}+\dfrac{F_{ax,Rk}}{4} \end{cases}$$

where $F_{v,Rk}$ is the characteristic load capacity per shear plane per fastener (kN); $f_{h,k}$ is the characteristic embedment strength (kN/mm); d is the fastener diameter (mm); t_1, t_2 are the timber or board thickness or penetration depth (mm); β is the ratio between the embedding wood strength of the joint components 1 and 2, $f_{h,2,k}/f_{h,1,k}$; $M_{y,k}$ is the characteristic fastener yield moment (in this study, it can be assumed as M_y = 40 050 Nmm, from Table 1); and $F_{ax,Rk}$ is the characteristic axial withdrawal capacity of the fastener (for dowels it is null). Note that, in the absence of results for bending tests on the wooden dowels, EYM suggests using an expression $\pi/32(s_B d^3)$, where s_B is the bending strength of the wood species (230.83 MPa for massaranduba, in accordance with NBR (1997)).

Blass *et al.* (1999), as a result of research conducted on connections with wooden dowels, proposed that the shear load-carrying capacity R_k should be calculated by:

$$4.\quad R_k = \sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_{u,k}\delta f_{h,k} d}$$

$$5.\quad M_{u,k} = \frac{f_{m,k}\pi d^3}{32}$$

where β is the ratio between the embedding wood strength of the joints components 1 and 2, $f_{h,2,k}/f_{h,1,k}$; δ is a reduction coefficient (a value of 0.75 is recommended); $M_{u,k}$ is the bending moment of the dowel; $f_{h,0,k}$ is the embedding strength according to Equation 5; and $f_{m,k}$ is the bending strength of the dowel (230.83 MPa for massaranduba in accordance with NBR (1997)). In this study, $M_{u,k}$ can be assumed as equal to the experimental value of M_{max} = 49 695 Nmm from Table 1.

More recently, Milch *et al.* (2017) validated some empirical expressions to predict the load-carrying capacity of single-shear dowel-type joints, per shear plane, loaded laterally to their axis as proposed by Fukuyama *et al.* (2008) based on EYM.

$$6.\quad P_{y,EYM,cal} = \sqrt{\frac{4dF_{ecp}M_p\beta}{1+\beta}}$$

$$7.\quad F_{ecp} = \min(F_{e,exp},\ \alpha_F F_{cvf}))$$

8. $$F_{\mathrm{e,exp}} = \frac{P_{\mathrm{max,exp}}}{dL_1}$$

9. $$M_{\mathrm{p}} = \frac{\pi d^3}{32} F_{\mathrm{b}}$$

where F_{ecp} is the embedment strength; $F_{\mathrm{e,exp}}$ is the embedment strength in joint components (N/mm^2) (it can be assumed equal to the experimental values of Table 4 for $f_{\mathrm{h,0}}$); α_{F} is an amplification coefficient on embedment yield stress (suggested as 1.9); F_{cvf} is the embedment yield stress in the dowel (can be assumed as equal to 110.4 N/mm^2 in accordance with the previous experimental campaign conducted by Pereira (2016)); β is the ratio between embedding wood strength of the joint components 1 and 2; M_{p} is the plastic capacity of the dowel (in this study it can be assumed as $M_{\mathrm{max}} = 49\ 695$ Nmm); $P_{\mathrm{max,exp}}$ is the experimental maximum force (N); and F_{b} is the bending strength of the dowel (230.83 MPa for massaranduba in accordance with NBR (1997)).

Table 5 presents the comparison between the tests results and the theoretical calculations for the load-carrying capacity of the dowel-type joints. Only the joint specimens with a reference moisture content of 12% are analysed. For the calculation, whenever possible, experimental values collected in the previous steps of the research were used (e.g. embedment strength, bending moment of the dowel, etc.). The values presented in parentheses used only theoretical values, based on the different expressions proposed by the models, and ignoring the tests results presented in Sections 2.1 and 2.2.

It can be noted that Eurocode 5 underestimates the resistance of the connections in all cases. This can be attributed to the fact that this code does not consider wooden dowels. The best theoretical prediction is given by Fukuyama *et al.* (2008), where the numerical values are slightly higher than the experimental ones. However, the model by Fukuyama *et al.* (2008) is not sensitive to the variation of the density of the connected wooden elements demonstrated by the experimental results. In fact, it is the embedment yield stress in the dowel (F_{cvf}) that, according to this model, is governing the final result. It is important to note that this value was obtained experimentally in a previous step of the research by Pereira (2016).

4. Conclusions

There is a significant lack of guidelines to predict the behaviour and load-carrying capacity of dowel-type joints connected with wooden dowels. Moreover, the effect of moisture content on the load-carrying capacity of these joints has not been addressed accurately.

In the present research, an experimental campaign with the aim of addressing this shortcoming was presented. The test results proved the relevance of employing this type of dowels in terms of resistance, properties and the overall behaviour of the connection. Therefore, the response of timber joints connected by wooden dowels was analysed and the reliability of the expressions available to predict their load-carrying capacity was assessed.

The experimental work showed that the properties and behaviour of the connection assessed through the available numerical expressions diverge significantly from the test results. The current version of Eurocode 5 only mentions metallic dowels, and employing its expressions proved to underestimate the resistance of the connections. Moreover, the experiments showed that the behaviour of a dowel-type timber-to-timber joint diverges when a wooden dowel is used instead of a steel one; even the embedment strength is different between a wooden and a steel dowel. The expressions proposed by Fukuyama *et al.* (2008) present accurate results for a moisture content of 12%, but they are not sensitive to density. This indicates that further analyses and research studies are needed to improve the analytical models, or even suggest ones, to predict the load-carrying capacity of dowel-type joints connected by wooden dowels. Furthermore, as expressed in the results, it can be clearly seen that these particular dowel-type joints depend on the mechanical properties of the connected elements (size and density) and environmental conditions (moisture content); hence, the analytical expressions should consider these characteristics.

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