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MODIFIED WOOD AS COMPRESSION REINFORCEMENT OF TIMBER PERPENDICULAR TO THE GRAIN

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ABSTRACT: An investigation was carried out to examine the potential to utilise modified wood as a reinforcement for timber subjected to compression loading perpendicular to the grain. In recent years there has been a significant number of studies examining the use of steel screws and bonded in rods for this purpose. This is becoming more and more important with the increased use of timber in medium-to high rise structures. In this study, thermally densified or modified timber in the form of dowels are utilised as compression reinforcement perpendicular to the grain and tested to failure. Thermally densified dowel reinforcement arrangements of 2, 4, and 6 dowels are examined experimentally under a compressive load and compared to timber samples similarly reinforced but with steel screws specifically designed to resist stresses perpendicular to the grain. The results have demonstrated the potential to utilised modified wood to create an all-wood solution to reinforce against compressive stresses perpendicular to the grain.

KEYWORDS: Compressed Wood, Modified Wood, Reinforcement, Perpendicular to Grain, Eurocode 5.

1 INTRODUCTION

The aim of this research is to investigate a sustainable alternative to current methods of reinforcement of timber elements perpendicular to the grain. There has been a significant amount of innovation in the timber industry in recent decades that has resulted in the increased use of timber in medium- to high-rise construction. Advances in engineered wood products and connection systems have allowed timber to rival more commonly-used construction materials and to meet the structural demands of modern construction.

The use of reinforcement in the form of glued-in rods or screws in timber structures has also helped advance the possibilities when it comes to building with timber. Currently, the use of glued-in rods or steel screws as reinforcement is not prescribed in Eurocode 5 [1]. Their use is governed by European Technical Approvals (ETAs), which are supplier-specific [2]. Recent developments, which are well described in the literature [3–6], allow for the reinforcement of timber perpendicular to the grain using self-tapping screws. These methods can also be used to reinforce notches, holes in beams, or to reinforce against tension stresses perpendicular to the grain in curved or pitched cambered beams, for example [4–6]. The use of reinforcement is due to be prescribed in the next generation of Eurocode 5, which is currently under development [7].

While self-tapping screws are a simple economic method of reinforcing timber, this approach relies on the use of non-sustainable, carbon-intensive steel, which may be ultimately underutilised in terms of stress. In this study, timber elements reinforced perpendicular to the grain with densified wood (DW) dowels are compared with those reinforced with steel screws. Densified wood dowels are made from softwoods that have been radially compressed under heat and pressure, which enhances their structural properties, and they have been shown to have excellent properties when used in timber connections [8,9]. Test configurations with 2, 4 and 6 screws/dowels are examined and compared to unreinforced timber specimens. The potential to utilise densified wood is examined, and experimental results are compared to the analytical equations in Eurocode 5.

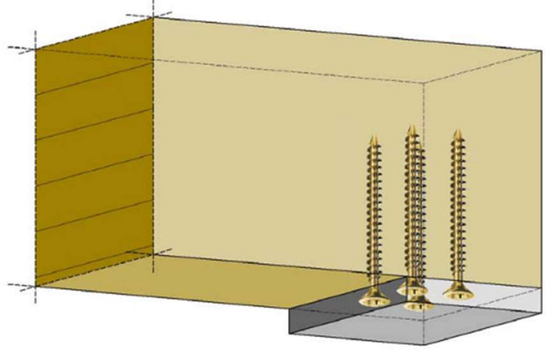

Figure 1: *Screw reinforcement arrangement at support* [3]

2 MATERIALS & METHODS

2.1 TIMBER

The timber material used in this study was Douglas fir grown in Ireland. The density and dynamic modulus of elasticity of the sawn boards were assessed, and glued

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laminated members were designed and manufactured so as to minimise the variation of elastic modulus and density between the specimens. The laminates were glued together using a one-component PU adhesive and were clamped in a rig to a minimum pressure of 0.6 MPa. All the specimens were conditioned at a temperature of 20 ± 2˚C temperature and 65 ± 5 % relative humidity prior to testing. Test specimens, 300 mm in length, were cut from the manufactured glued laminated members and were accurately prepared to ensure that the loaded surfaces were plane and parallel to each other.

2.2 SCREW REINFORCEMENT

The screws utilised in this study are 9 mm diameter VGS screws with a length of 100 mm supplied by Rothoblaas. These screws are specifically designed to reinforce timber elements subjected to compressive stresses perpendicular to the grain and their use in timber structures is governed by ETA-11/0030 [10]. Pre-drilling of the timber was required as the screw diameter is greater than 6 mm, but the diameter of the pre-drilling holes could not be greater than 5.6 mm in accordance with Eurocode 5 [1]. The holes were drilled with a 5 mm diameter drill bit to a depth of 100 mm. The fully threaded self-tapping steel screws were screwed into the timber until the countersunk head was flush with the surface of the timber specimen.

2.3 DENSIFIED WOOD REINFORCEMENT

The densified timber utilised in this study was manufactured from Scots Pine (Pinus Sylvestris) wood. The timber was thermally compressed in the radial direction to a compression ratio of approximately 54% at the University of Liverpool. The dowels were manufactured by heating the dowels to 130˚C over a 1-hour period and then compressing the timber at this temperature for 1-hour. The dowels were then cooled under pressure until the temperature was less than 66˚C [8]. This resulted in a final mean density ranging between 1100-1500 kg/m^3. The DW dowel diameter used was 10 ± 0.5 mm and the dowel length was 100 mm.

Figure 2: *DW specimen preparation*

Specimen preparation can be seen in Figure 2. The specimens were predrilled with a 10.5 mm diameter drill bit to a depth of 100 mm. A one-component PUR adhesive was applied evenly on the surface of the dowels and in the predrilled holes. The densified wood dowels were then inserted into the predrilled holes and the adhesive was allowed to cure. The dowels were cut at the surface of the timber specimen and sanded to ensure a flush finish between the dowel and timber surfaces.

2.4 LOAD CARRYING CAPACITY

The compressive strength of a material is its ability to resist compressive forces. When a load above the elastic limit is applied to a timber element perpendicular to the grain the stresses cause the longitudinally orientated fibers of the timber to collapse. This can cause densification and increased compressive strength but also causes permanent deformation. The compressive strength of a timber element typically depends on its density and the denser the timber the higher the compressive strength. Characteristic compressive strength perpendicular to the grain can be estimated at 10% to 20% of the parallel to the grain compressive strength or at 0.007 times the density of the timber for softwoods [11].

The compressive strength perpendicular to the grain of a timber element, $f_{c,90}$, can be determined from Equation (**1**) in accordance with the European standard EN 408 [12].

$$f_{c,90} = \frac{F_{c,90,max}}{bl} \quad (1)$$

where b is the width and l is the length of the specimen and the force $F_{c,90,max}$ is be determined from the load-deformation curve, constructed as shown in Figure 3, where h_t is the gauge length.

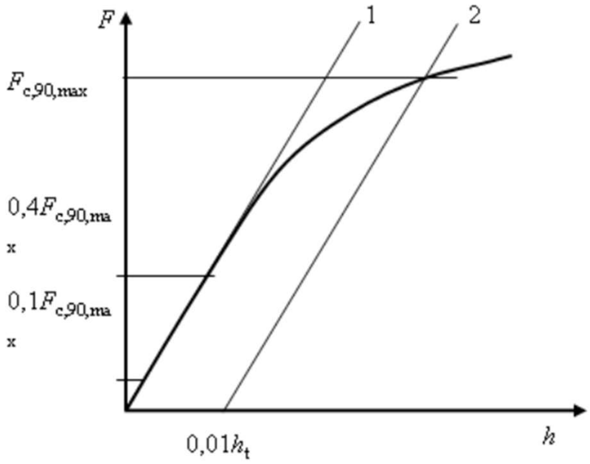


Figure 3: *Load-deformation curve* [12]

To distribute the perpendicular to the grain stresses throughout the section, a timber element can be reinforced by using screws or dowels inserted into the section perpendicular to the grain to improve stress dispersion into the timber [10]. This reinforcement will prevent early cracking, increase the load-bearing capacity perpendicular to the grain, decrease deformation and increase stiffness. Reinforcement against perpendicular to the grain stresses can be an important design requirement at end-bearing supports, internal supports, at notches and holes within structural timber elements. Buckling and pushing-in failure are the two types of failure modes associated with screw reinforcement subjected to compressive stresses perpendicular to the grain [7,10,13].

2.5 DESIGN OF COMPRESSION REINFORCEMENT

For the purpose of developing a modern design standard, the CEN standardisation committee TC 250 has established a Working Group 7 “Reinforcement” to investigate current technologies for the new generation of Eurocode 5. Dietsch [7] provides a description of the work items, work plan, structure, design approaches and background information with regard to the new section of the proposed Eurocode 5. The committee is examining the use of reinforcement of timber in curved beams, notches and holes, connections and support sections subjected to compression perpendicular to the grain. Equation (2) is the method proposed for the new section of Eurocode 5 to specify the design of reinforcement of members under compression perpendicular to the grain [9] (also see technical assessment ETA-11/0030 [10]).

$$F_{c,90,Rk} = min\begin{cases} k_{c,90} \cdot b_c \cdot l_{ef,1} + n \cdot min\,(F_{ax,\alpha,Rk}; F_{b,Rk}) \\ b \cdot l_{ef,2} \cdot F_{c,90,k} \end{cases} \quad (2)$$

where:

$k_{c,90}$ = Compression factor according to 6.1.5.1 in [1]
b_c = Contact width
$l_{ef,1}$ = Effective length parallel according to 6.1.5 in [1]
n = Number of screws
n_0 = Number of screws in rows parallel to the grain
$F_{ax,\alpha,Rk}$ = Pull through capacity according to [10]
$F_{b,Rk}$ = Buckling capacity according to [10]
b = Width of the beams
$l_{ef,2}$ = Effective distribution length [1]

3 EXPERIMENTAL PROGRAMME

The test programme comprised 35 compression test specimens within 7 test series/configurations as seen in Table 1. There are 5 repetitions of each test configuration. This results in 5 unreinforced specimens, 15 reinforced with steel screws and 15 reinforced with DW dowels.
In preparing the timber specimens, efforts were made to reduce the inherent variability in material properties between specimens, particularly density as there is a strong relationship between the bearing capacity of timber and its density. As a result, statistical Student’s t-tests were carried out to compare the mean density results of each test series and it was shown that there was no statistical difference between the mean density of each series. This means, that any significant increase in bearing capacity observed in the experimental results is likely due to the reinforcement configuration and not due to variations in density.

Table 1: *Test programme*

Specimen	Reinforcement	n
Unreinforced	-	5
Reinforced 2 screws/dowels	Steel	5
	DW	5
Reinforced 4 screws/dowels	Steel	5
	DW	5
Reinforced 6 screws/dowels	Steel	5
	DW	5

3.1 TEST PROCEDURE

The test procedure was based on an extensive review of the literature and the test procedure specified in EN 408 [12] related to the evaluation of compressive strength of glued laminated elements perpendicular to the grain. A common bearing area (120 x 120 mm^2) was used in all tests to focus on the influence of the reinforcement. Each specimen was centrally loaded with a constant crosshead movement to ensure failure is achieved in 300 ± 120s. Two linear variable displacement transformers (LVDTs) were located centrally on either side of the specimen over a gauge length of 0.6 x the height of the specimen to determine the stiffness of the reinforcing scheme.

4 RESULTS

4.1 UNREINFORCED TEST RESULTS

The unreinforced test series results are shown in Table 2 and the corresponding load-deformation curves are shown in Figure 4. The results show a mean value for $F_{c,90,max}$ of 123.6 kN, for $f_{c,90}$ of 8.6 N/mm^2 and for $E_{c,90}$ of 1841.3 N/mm^2. These values have standard deviations of 28.2 N/mm^2, 2.0 N/mm^2 and 598.9 N/mm^2, respectively. The mean results for the unreinforced series will be used as a basis for comparison for the reinforced test results.

Table 2: *Unreinforced test series results*

Series	$F_{c,90,max}$ (kN)	$f_{c,90}$ (N/mm^2)	$E_{c,90}$ (N/mm^2)
Mean	123.6	8.6	1841.3
S.D	28.2	2.0	538.9

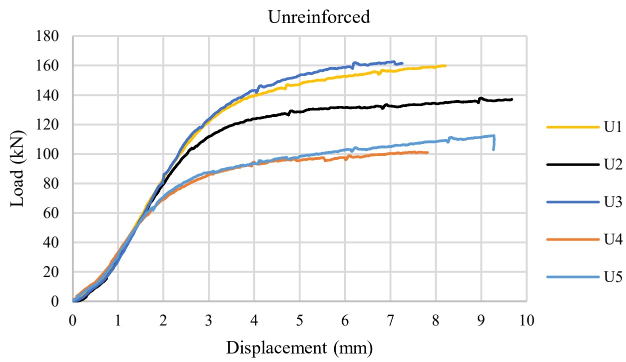


Figure 4: *Unreinforced specimens load-deformation curves*

The difference in results for the unreinforced specimens was due to variability in the properties of the timber and especially the density. For example, U3 had the highest capacity and also had the highest density while U4 had the lowest capacity and the lowest density.

4.2 SCREW REINFORCEMENT RESULTS

The experimental results have demonstrated a significant improvement in compressive strength that can be achieved with the use of steel screws. The load-deformation results for specimens reinforced with 6, 4 and 2 screws can be seen in Figure 5. The mean results from screw reinforced compression tests can be seen in Table 3. The results of the experimental tests have shown an increase in mean strength of 64% over the unreinforced series for specimens reinforced with 6 screws and a mean stiffness increase of 84%. By comparison, the results for specimens reinforced with 4 screws showed an increase in mean strength of 41% and an increase in stiffness of 52%. Specimens reinforced with only 2 screws also demonstrated a significant increase in mean strength of 21% over the unreinforced series and an increase of 14% in mean stiffness.

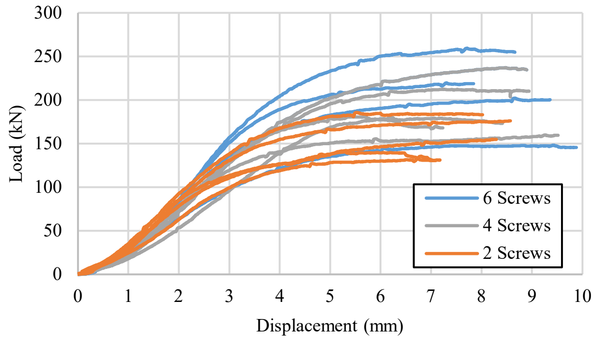


Figure 5: *Load-deformation for specimens reinforced with 6, 4 and 2 screws*

Table 3: *Mean test results for screw reinforced specimens*

Series	$F_{c,90,max}$ (kN)	$f_{c,90}$ (N/mm^2)	$E_{c,90}$ (N/mm^2)
6 screws	203.1	14.1	3385.1
S.D.	42.3	2.9	1923.7
Increase	64%	64%	84%
4 screws	174.5	12.1	2796.9
S.D.	23.0	1.6	1349.9
Increase	41%	41%	52%
2 screws	150.0	10.4	2095.6
SD	24.5	1.7	554.8
Increase	21%	21%	14%

4.3 DENSIFIED WOOD REINFORCEMENT RESULTS

The results have shown that there is also a significant improvement in the compressive stiffness and strength of timber specimens reinforced with densified wood dowels. The load-deformation results for specimens reinforced with 6, 4 and 2 DW dowels can be seen in Figure 6.

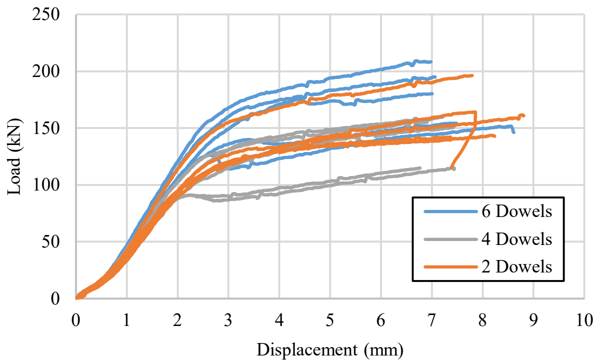
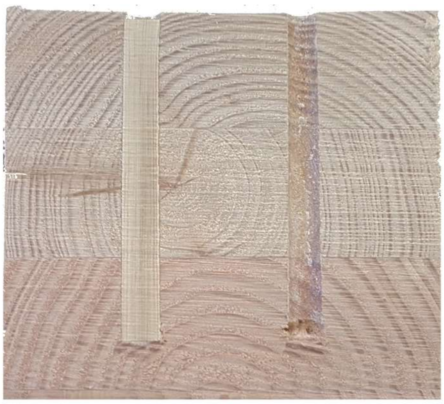


Figure 6: *Load-deformation for specimens reinforced with 6, 4 and 2 densified wood dowels*

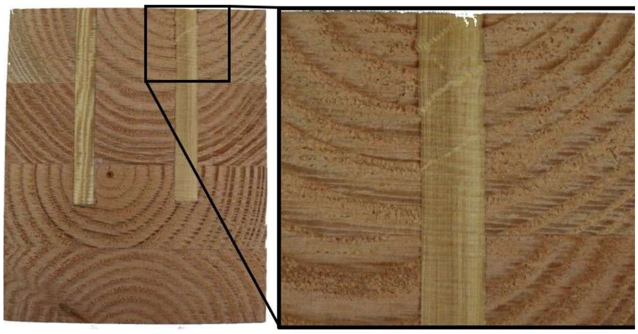
The mean results of the DW dowel reinforced compression tests are presented in Table 4. The results of the experimental tests show an increase in mean strength of 30 % for specimens reinforced with 6 DW dowels when compared to the unreinforced series and a mean stiffness increase of 37%. Specimens reinforced with 2 DW dowels had an increase in mean strength of 16% over the unreinforced series and an increase of 20% in mean stiffness. Unexpectantly, the results for specimens reinforced with 4 DW dowels showed no increase in mean strength and only 18% difference in mean stiffness. An investigation into the failure of specimens reinforced with 4 dowels showed a lack of bond between the dowel and the inner surface of the timber in two specimens as seen in Figure 7a. As the cross-section was cut, the dowel separated from the timber with little effort. These specimens also showed large compression failures zones in the timber below the dowel indicating a failure of the bond and little composite action between the dowel and the timber. It is possible that there was excess dust from drilling or too smooth a surface post drilling, which adversely affected the adhesive bond. On the other hand, specimens with better bonds resulted in little to no compression damage at the bottom of the dowel as seen in Figure 7b. Figure 7b shows a specimen with a good adhesive bond between the timber and the dowel which has resulted in compression failure or buckling of the longitudinal fibers occurring within the DW dowel.

Table 4: *Mean test results for dowel reinforced specimens*

Series	$F_{c,90,max}$ (kN)	$f_{c,90}$ (N/mm^2)	$E_{c,90}$ (N/mm^2)
6 dowels	160.5	11.2	2501.8
S.D.	28.7	2.0	520.4
Increase	30%	30%	36%
4 dowels	122.4	8.5	2166.6
S.D.	25.8	1.8	261.6
Increase	-1%	-1%	18%
2 dowels	143.1	9.9	2087.1
SD	17.9	1.3	844.8
Increase	16%	16%	13%



a)



b)

Figure 7: *Experimental investigation, a) specimen with failure of the adhesive bond, b) specimen with good adhesive bond and compression wrinkle in the DW dowel*

4.4 COMPARISON OF RESULTS

To examine the suitability of this technology, it is important to compare the experimental results to the Eurocode design values. As the reinforcement of timber perpendicular to the grain is proposed to be included in the next generation of Eurocode 5, the design approaches presented by Dietsch [7] were used to calculate design values for both steel screws and DW dowel reinforcement.

Equation (2) previously presented was used to calculate the load-bearing capacity of the screw reinforced specimens. As seen in Figure 8, the results for the steel screw reinforced samples were greater than the design capacity results in all but one specimen.

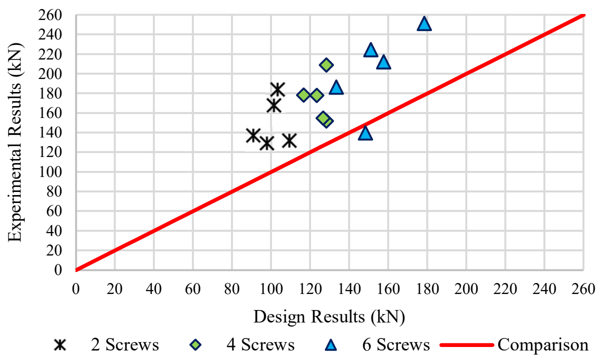


Figure 8: *Comparison of design and experimental results for screw reinforcement*

To estimate the load-bearing capacity of the test specimens reinforced with DW dowels, the equation used to estimate the capacity of steel screws was adapted. Equation (2) considers the minimum value of the strength of the timber and the strength of the screw/rod reinforcement [7,10]. This equation has been adapted as shown in Equation (3). The pull-through capacity, $F_{ax,\alpha,Rk}$ of the steel screw has been removed from the formula as it is not applicable for the calculation for DW dowel reinforcement resulting in the equation as shown in Equation (3).

$$F_{c,90,Rk} = min\begin{cases} k_{c,90} \cdot b_c \cdot l_{ef,1} + n * (F_{b,Rk}) \\ b \cdot l_{ef,2} \cdot F_{c,90,k} \end{cases} \qquad (3)$$

where $F_{b,Rk}$ is the bucking capacity of the DW dowel, n is the number of DW dowels and the other terms are as previously described. The DW dowel properties in the parallel to the grain direction are used in this study. Figure 9 shows a comparison between the characteristic design results and the recorded results from testing of the specimens reinforced with DW dowels. The graph shows that all specimens have a greater capacity than the design values except for two specimens with 4 dowels for which there were manufacturing defects in the test specimens (Figure 7a). Failure due to poor bond quality is not considered in the design equations. It is important to note that the experimental density of each specimen was used to calculate the respective design values instead of the characteristic density as would be normally used in design situations. The use of the characteristic density would improve the results but further tests are required to establish the characteristic values from experimental testing and it was deemed more conservative to use the experimentally determined density.

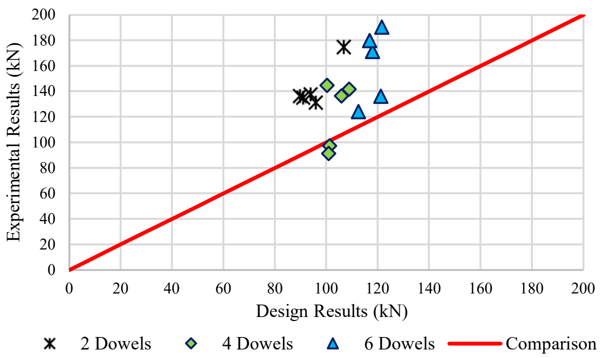


Figure 9: *Comparison of design and experimental results for dowel reinforcement*

When examining the percentage increase in stiffness of the different reinforcement configurations, it was shown that the overall stiffness of the screw reinforced specimens was significantly higher than that of the dowel reinforced specimens at higher loads but at lower load levels, the dowel reinforced specimens demonstrated better stiffness behaviour. This was also found by Crocetti et al. [14] who showed that wooden dowel reinforced beams had a better stiffness at low load levels when compared to steel dowel reinforced beams, however, steel-reinforced beams had better stiffness at higher loads. It was suggested that the variations in strength and stiffness at lower load levels were due to the difficulty in achieving a smooth finish between the steel dowel and the timber surface. Without a smooth flush finish between the steel and timber surfaces, the load will not be equally distributed between all dowels. A similar experiment conducted by Ed and Hasselqvist [15] confirms that the steel dowels were not perfectly flush with the timber surface after insertion.

5 CONCLUSIONS

An experimental investigation of timber specimens reinforced with self-tapping screws and densified wood dowels was completed. A total of 7 series and 35 specimens were tested with varying reinforcement configurations.

The results of the compression tests showed an increase in compressive strength of 16% for specimens reinforced with 2 densified wood dowels and an increase of 30% for specimens reinforced with 6 dowels. Reinforcement with densified wood dowels also resulted in increased stiffness with an increase of 13% for specimens with 2 dowels, 18% for specimens with 4 dowels and 36% for specimens with 6 dowels.

Bond failure was observed in a limited number of specimens for the series reinforced with 4 densified wood dowels. This series showed similar results to the unreinforced series. The issue may have been due to excess sawdust from drilling. Retesting of this series is required to examine this further. The original results as they were recorded are presented.

The design equations, which have been put forward for reinforcement of timber with metal screws in the new Eurocode 5, were used to predict the load-bearing capacity for the specimens tested in this study. The results were shown to give good predictions of the load-bearing capacity. Densified wood dowels showed promising results for reinforcement against compression perpendicular to the grain stresses when compared to unreinforced specimens. More studies are required to further evaluate the performance of densified wood dowels as a possible reinforcement against stresses perpendicular to the grain. Also, an investigation is required to evaluate efficient and effective means of bonding the dowel into the timber element, which would compete with the ease of handling of the self-tapping steel screws.

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