Reinforcement of Timber Elements in Compression Perpendicular to the Grain using Compressed Wood Dowels

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ABSTRACT: In the past decade, there has been an increased focus on the environmental impacts of construction and a movement towards more sustainable construction products. Timber is one such sustainable product that can achieve these environmental targets but, while timber has a high strength-to-weight ratio parallel to the grain, it demonstrates poor strength perpendicular to the grain. As a result, stress perpendicular to the grain is an important factor in the design of timber structures, especially in areas of concentrated loading, such as supports. This paper describes a study, which examines the use of compressed wood dowels as a sustainable alternative to the self-tapping steel screws for reinforcement against perpendicular to the grain compressive stresses. Glued laminated timber specimens were reinforced with 2, 4 and 6 dowels using the same arrangement and dimensions as outlined in Eurocode 5 for self-tapping steel screws. The results show a significant improvement in both load-bearing capacity and stiffness. When compared to the unreinforced condition, the results showed an increase in load-carrying capacity of up to 30% for the 6 dowels arrangement. An increase in stiffness of up to 36% for 6 dowels arrangement was also observed. Additionally, good agreement was found when comparing the experimental results to design equations adapted from recently proposed Eurocode 5 recommendations for compression reinforcement using self-tapping steel screws.

KEYWORDS: Compressed wood dowels; Reinforcement; Stresses perpendicular to the grain; Glued laminated timber.

1 INTRODUCTION

With the increased focus in recent years on global warming and the impact of human activities on the environment, it has brought an expectation on the construction industry to reduce its carbon footprint. This has seen a considerable body of research into the development of timber structures as a sustainable alternative to steel and concrete. These studies have investigated different technologies and materials to develop highly engineered timber products to achieve increased load-bearing capacity and stiffness.

Timber is one of the oldest building materials and is a natural renewable material. As a natural material, timber has varying properties depending on age, species of wood from which it has been harvested and many to other variables. By enhancing these properties, a more reliable and less variable material can be produced for construction. Timber has good strength parallel to the grain but demonstrates poor strength perpendicular to the grain. As a result, stress perpendicular to the grain is an important factor in the design of timber structures and these stresses need to be taken into consideration in the design process, especially in areas of support [1].

Compressive stresses perpendicular to the longitudinal fibres of the timber cause the fibres to compress, which can lead to large deformations. The calculation of compressive strength perpendicular to the grain from experimental methods has been widely debated over the past decade with many models proposed for calculating the design capacity. This has led to different test methods according to ASTM, ISO and CEN [1][2]. More recent developments, which are well described in the literature [3], [4] and [5], allow for the reinforcement of timber perpendicular to the grain using self-tapping screws.

Self-tapping screws are a simple economic method of reinforcing timber and can be used for reinforcing against compression, tension, and shear stresses. This approach relies on the use of non-sustainable, carbon-intensive steel, which may be ultimately underutilised in terms of stress. The purpose of this research is to investigate the use of compressed timber dowels as a possible sustainable alternative to self-tapping steel screws against compressive stresses perpendicular to the grain. Compressed wood dowels are made from softwoods, which are compressed under heat and pressure which enhances their structural properties, and have been shown to have excellent properties when used in timber connections [6,7].

2 COMPRESSION PERPENDICULAR TO THE GRAIN

2.1 *Compressive Strength*

The compressive strength of a material is its ability to resist compressive forces. When a load 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 [8].

2.2 *Load Carrying Capacity*

The compressive strength perpendicular to the grain $f_{c,90}$, can be determined from Equation (1) in accordance with the

European standard EN 408 [9]. Using results from the compression tests outlined in this standard, Section 16.2, a load-deformation curve is constructed as shown in Figure 2.1. Using this curve, the force $F_{c,90,max}$ can be determined and hence the compressive strength of a timber element perpendicular to the grain.

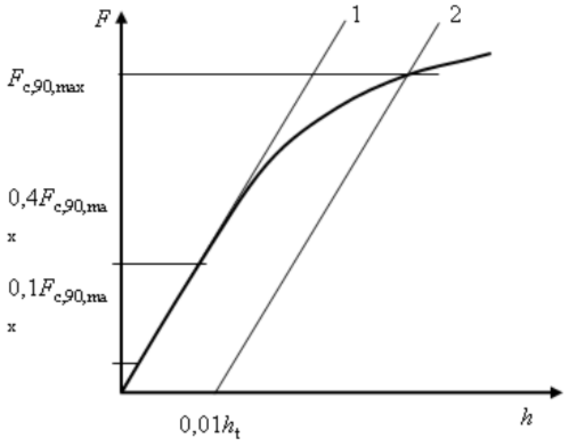

Figure 2.1 Load-deformation curve [7]

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

where b is the width and l is the length of the specimen. To distribute the perpendicular to the grain stresses throughout the section, the 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, will decrease deformation and increase stiffness. Reinforcement against perpendicular to the grain stresses can be important design requirements at end bearing supports, internal supports, at notches and holes within structural timber elements.

2.3 *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 [10] 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 [11]).

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

where:
$k_{c,90}$ = Compression factor according to 6.1.5.1 in [12]
b_c = Contact width
$l_{ef,1}$ = Effective length parallel according to 6.1.5 in [12]
n = Number of screws
n_0 = Number of screws in rows parallel to the grain
$F_{ax,\alpha,Rk}$ = Pull through capacity according to [11]
$F_{b,Rk}$ = Buckling capacity according to [11]
b = Width of the beams
$l_{ef,2}$ = Effective distribution length [12]

3 DOWELS AS COMPRESSION REINFORCEMENT

A study completed by Crocetti et al. [13] showed that the 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 [14] confirms that the steel dowels were not perfectly flush with the timber surface after insertion, which also had an effect on the results at early loading stages. In contrast, wooden dowels are flush with the timber surface ensuring all dowels engaged simultaneously under loading conditions. Overall, it was shown that steel dowels provided a higher load-carrying capacity but also a greater variance in the final load-carrying capacity.

The slenderness ratio or length of dowel compared to the dowel diameter was shown to have a significant effect on the load-carrying capacity. In the study by Ed and Hasselqvist [14], the reinforcement length used was 400 mm, which is over 21 times the diameter of the 19 mm dowels; however, it was suggested by Jung at el. [15] that the optimum length for reinforced dowels is 10 times the diameter based on tests conducted on Japanese Cedar compressed dowels. Limiting the slenderness ratio of the dowel can prevent buckling of the dowel reinforcement. An agreement on a universal design standard for glued-in-rods (GIR) for reinforcement of timber beams has yet to be achieved [16].

4 COMPRESSED WOOD DOWELS

Compressed wood dowels have proved to be an attractive environmentally friendly alternative to metallic fasteners such as self-tapping steel screws. The compressed wood used in this study was produced by thermal compression of softwood timber to increase its density, strength, stiffness, hardness and reduce porosity [6].

Compressed wood dowels showed good properties when tested in shear and when compared with other standard hardwood dowels. As the density of the dowel is increased, the results show a proportional improvement in stiffness, yield load and maximum load and in contrast, the plastic modulus decreases [17]. Compressed wood dowels used in post-and-beam connections showed very good properties in resisting pull-out and moment rotation forces and demonstrated the potential for this type of modified timber material could be used for structural purposes such as long-span frame structures and has the potential to be further optimised [18].

Compressed wood dowels and compressed wood plates used to replace steel dowels and steel plates in a moment-resisting connection were tested to evaluate the possible replacement of steel with a more environmentally friendly option. Results on a spliced beam-beam moment-resisting connection show a failure load of just 20.3% less for the compressed wood connection when compared to connections with equivalent steel fasteners and 18.6% less in stiffness. Failure modes for both reinforcement methods were similar [6].

Engineered wood products give a more sustainable alternative to the use of more traditional construction materials such as steel and concrete. The use of compressed wood products has shown to have the potential to be a sustainable and economic alternative to metal fasteners and hardwood dowels [19]. The compressed wood, with enhanced properties over standard hardwood dowel, also has a spring-back effect which means it will expand over time resulting in a tight fit connection which may be a beneficial characteristic in many structural timber engineering applications.

5 TESTING

5.1 Test Programme

The experimental test programme consists of 20 compression tests which are split into 4 series comprising 5 test specimens each. The first five tests were conducted on unreinforced timber specimens which will form a basis for comparison. Fifteen tests were conducted on timber specimens reinforced with compressed wood dowels. The compressed wood dowels have a 10 mm diameter with a length of 100 mm. These are split into 3 test series with five specimens reinforced with two dowels, five specimens reinforced with four dowels and five specimens reinforced with six dowels as shown in Figure 5.1.

5.2 Compressed Wood Dowels

The compressed wood dowels were manufactured using Scots Pine (Pinus Sylvestris) wood, compressed in the radial direction with a compression ratio of approximately 54% at the University of Liverpool. The dowels were manufactured by compressing and heating the dowels to 130˚C over a 1-hour period and then held at this temperature under pressure for 1-hour. The dowels were then cooled under pressure until the temperature was less than 66˚C [6].

5.3 Specimen Preparation

The glued laminated timber beams used in this study were manufactured using Irish-grown Douglas Fir (Pseudotsuga menziesii). The beams were placed in a controlled climate chamber at a temperature of 20˚C and 65% relative humidity until the mass difference recorded over a 6-hour period was less than 0.1% in accordance with the requirements of EN 408 [9]. 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 compressed 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. Specimen preparation can be seen in Figure 5.2.

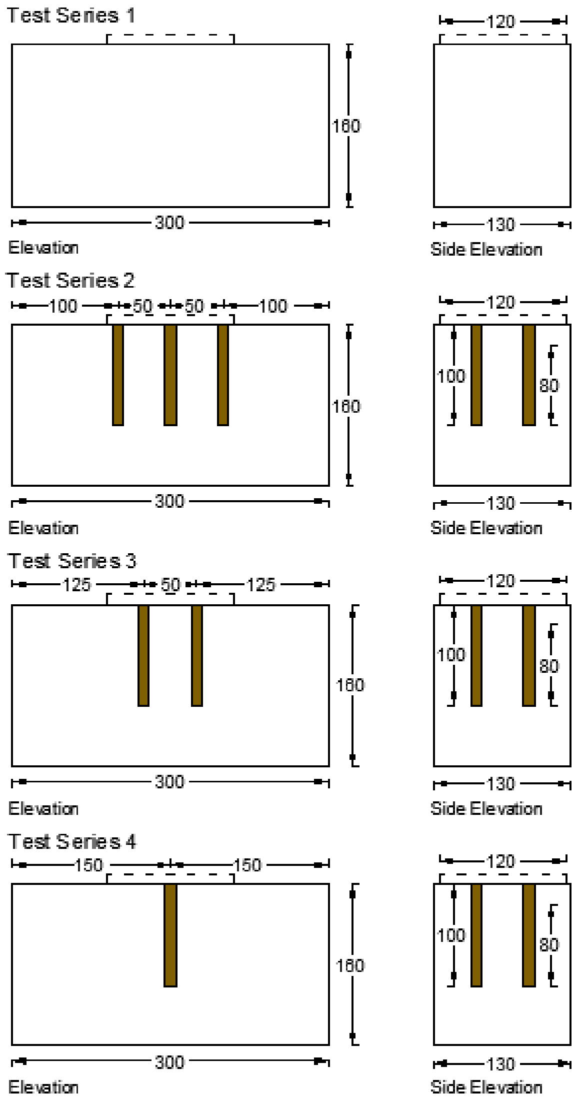

Figure 5.1 Specimen Layout

Figure 5.2 Specimen preparation

5.4 Statistical Analysis

Statistical tests were carried out to examine the distribution of the timber specimens for each series. There is a relationship between the load-bearing capacity of timber and timber density and as a result, statistical methods were implemented to ensure the distribution of the density is similar for each series prior to reinforcement. Therefore, the difference in results from a reinforced series should represent the effect of the reinforcement on the load-bearing capacity of the timber member [20].

There were three types of statistical tests performed on the test series. The Shapiro Wilks test checked for normality and showed each series to be normally distributed. The Levene's test examined the homogeneity of each series or the variance within the series and showed no significant difference in the variance between each series. As a result, the Student's t-test was carried out to examine the mean density of each series and showed no significant difference in means between each series. In this study, all statistical tests were carried out to a significance level of 0.95 (α = 0.5). The formation of each series, statistically equal in terms of the mean density, formed a basis for the comparative study of the different reinforcement arrangements.

6 PRELIMINARY TEST RESULTS

Before the testing commenced, preliminary tests were conducted on unreinforced specimens and dowelled specimens with no adhesive. These tests were required to establish the correct loading rate as per the EN 408 [9] and to highlight any major concerns before the test programme began. The results of these tests showed that a loading rate of 1.6 mm per minute would induce failure with the required time of 300 ± 120 s. The preliminary tests showed a lack of friction between the compressed wood dowels and the timber elements, which resulted in very little of the load being redistributed along the length of the dowel and most of the load being applied at the base of the dowel as shown at location A in Figure 6.1. To help distribute the load throughout the timber, adhesive was added to the dowels before insertion into the timber. This helped with the load redistribution and reduced the compression at the base of the dowel shown at point B in Figure 6.1. In the adhesively bonded specimen, failure and compression wrinkling were observed in the compressed wood dowel as shown at point C of Figure 6.1.

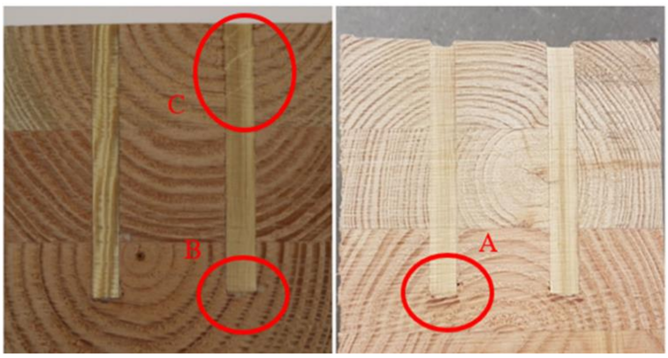

Figure 6.1 Cross-section from two test specimens

7 RESULTS AND ANALYSIS

7.1 Density and moisture content

Density tests were conducted on all 20 timber specimens. The density ranged from 481.9 kg/m^3 to 663.4 kg/m^3 with a mean density of 556.2 kg/m^3 and a standard deviation of 40.3 kg/m^3. Density tests also conducted on the compressed wood dowels. The density ranged from a minimum density of 1132.4 kg/m^3 to a maximum density of 1437.9 kg/m^3. The mean density of the dowels was 1253.8 kg/m^3 with a standard deviation from the mean of 66.1 kg/m^3.

Moisture content tests were conducted on all specimens after the compression tests were completed in accordance with EN 13183-1 [21]. The results of the test showed that the test specimens had a moisture content ranging between 11.3% and 13.2% with a mean moisture content for all s specimens of 12.3%. The moisture content results had a standard deviation of 0.5% of the entire test programme.

7.2 Compression test on the unreinforced series

The unreinforced test series results are shown in Table 7.1 and the corresponding load-deformation curves are shown in Figure 7.1. The results show an average 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 a standard deviation 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 7.1 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

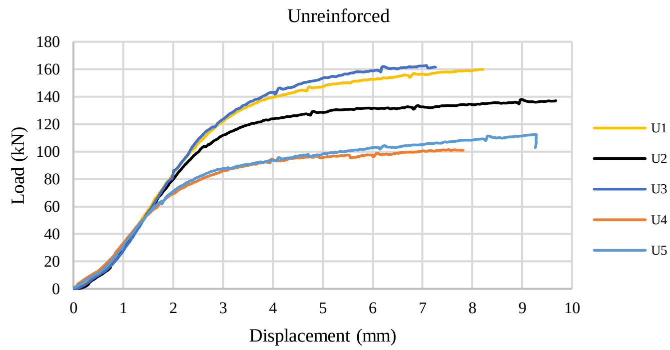

Figure 7.1 Unreinforced specimens load-deformation curves

The difference in results for the unreinforced specimens was due to variability on 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.

7.3 Compression test on the reinforced series

There were 15 compression tests completed for specimens reinforced with compressed wood dowels. The load-deformation curves for these reinforced specimens are shown in Figure 7.2, Figure 7.3 and Figure 7.4 for specimens reinforced with 6, 4 and 2 compressed wood dowels, respectively.

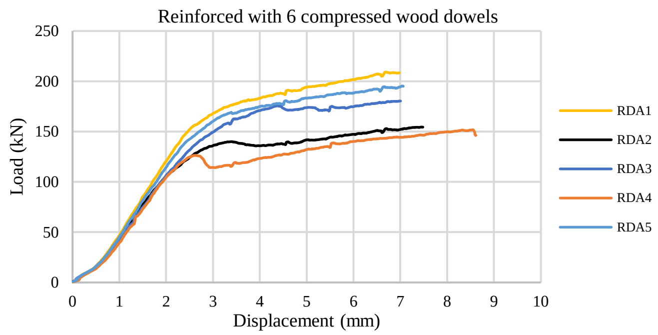

Figure 7.2 Load-deformation for specimens with 6 dowels

Figure 7.3 Load-deformation for specimens with 4 dowels

Figure 7.4 Load-deformation for specimens with 2 dowels

The results of the experimental tests show an increase in mean strength over the unreinforced series of 30% for specimens reinforced with 6 compressed wood dowels and a mean stiffness increase of 37%. The results for specimens reinforced with 4 compressed wood dowels showed no increase in mean strength and only 8% difference in mean stiffness. Specimens reinforced with 2 compressed wood dowels had an increase in mean strength of 16% over the unreinforced series and an increase of 20% in mean stiffness. The mean results from reinforced compression tests can be seen in Table 7.2.

An investigation into the failure of specimens reinforced with four dowels showed a lack of bond between the dowel and the timber as a cross-section was cut through the specimens and the dowel separated from the timber with little effort. These specimens also showed large compression zones below the dowel while specimens with better results had little to no compression zone at this location. Figure 7.5 shows a specimen with a failed bond between the timber and the dowel. It is possible that there was excess dust from drilling or too smooth a surface post drilling which could have affected the bonding.

Table 7.2 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%

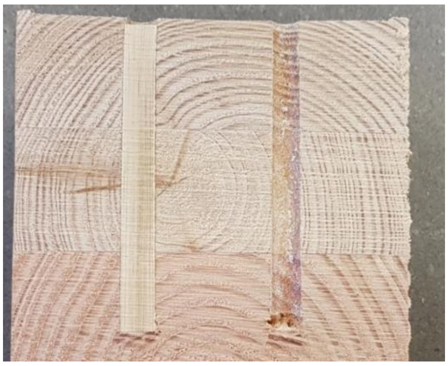

Figure 7.5 Specimen with failure of the adhesive bond

A significant increase in mean stiffness was recorded in series reinforced with 2 and 6 compressed wood dowels. The series with 4 compressed wood dowels showed only small increases, again because of the failure in the bond. The increase in stiffness was 20% for the series reinforced with 2 dowels and 37% for the series reinforced with 6 dowels.

8 DESIGN EQUATIONS

For the estimation of the load capacity of the series reinforced with compressed wood dowels, the equation used for the estimation of the steel screws was used. Equation (2) considers the minimum value of the strength of the timber and the strength of the compressed wood dowel. The properties of the compressed wood dowel used in the equations are in parallel to the grain. The pull-through capacity $F_{ax,\alpha,\mathrm{Rk}}$ of the steel screw has been removed from the formula as it is not applicable for the calculation for compressed wood dowel reinforcement, leaving the equation as shown in equation (3).

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

where $F_{b,Rk}$ is the bucking capacity of the compressed wood dowel, n is the number of compressed wood dowels and the other terms are as previously described. Figure 8.1 shows a comparison between the characteristic design results and the recorded results from testing. 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. Failure due to poor bond quality is not considered in the design equations. It is important to note that the experimental density of each specimens was used to calculate the respective design values instead of the characteristic density. The use of the characteristic density would improve the results but further tests are required to establish the characteristic values from experimental testing.

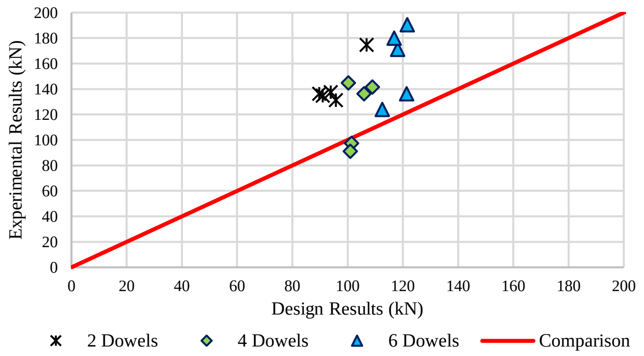

Figure 8.1 Comparison of design and experimental results.

9 CONCLUSION

An experimental investigation of timber specimens reinforced with compressed wood dowels was completed. A total of 4 series and 20 specimens were tested with varying quantities of compressed wood dowels.

The results of preliminary tests on unbonded compressed wood dowel reinforcement showed a lack of friction between the dowel and the timber even after expansion of the dowel. Thereafter, the dowels were adhesively bonded into the pre-drilled holes. The results of the compression tests showed an increase in compressive strength of 16% for specimens reinforced with 2 compressed wood dowels and an increase of 30% for specimens reinforced with 6 dowels. Reinforcement with compressed 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 number of specimens for the series reinforced with 4 compressed 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 first 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. Compressed 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 compressed 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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