Numerical Investigation of Reinforcement of Timber Elements in Compression Perpendicular to the Grain using Densified Wood Dowels

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HIGHLIGHTS

- The failure behaviour of densified wood dowel reinforced timber has been studied.
- A 3-dimensional numerical model utilising CZM to predict this behaviour is presented.
- A numerical parametric study has examined the influence of dowel diameter and length.
- A maximum dowel length-diameter ratio is recommended based on the numerical results.

ARTICLE INFO

ABSTRACT

In recent years, the construction industry has seen a greater focus on the use of sustainable construction materials to reduce the environmental impact of buildings. Timber is one such material that has seen a revival in its use due to its environmental credentials coupled with advances in the manufacture of engineered wood products and connection technologies. While timber and engineered wood products have a high strength-to-weight ratio suitable for large scale construction, timber is an orthotropic material and demonstrates poorer strength when loaded perpendicular to the grain. As a result, special consideration must be given to the design of areas of support where stress perpendicular to the grain develops in timber structures. This paper describes a study which examines the use of densified wood dowels as a sustainable reinforcement against perpendicular to the grain stresses using experimental and numerical approaches. Glued laminated timber samples were reinforced with 2, 4 and 6 densified wood dowels. The experimental results show significant improvements in load-bearing capacity can be achieved. A full 3-dimensional solid finite element model has been implemented in ABAQUS/Explicit software. The numerical model utilises cohesive zone modelling (CZM) and Hill plastic yield criterion to predict the failure behaviour of specimens utilising densified wood dowel reinforcement. The examined numerical modelling approach has been shown to give good predictions of the performance of the dowel-timber interaction and load-bearing capacity of the composite system. The numerical model has been also used in a parametric study to examine the influence of dowel diameter and dowel length on the failure behaviour. A maximum dowel length-to-diameter ratio is recommended based on the numerical results

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1. Introduction

In recent years, there has been a drive to reduce the impact of human activities on the environment and the construction industry is seen as a significant area in need of improvement. To improve the environmental credentials of construction, there has been an increased focus on the development of timber structures as a sustainable alternative to steel and concrete. There have been many studies that have investigated different materials and manufacturing procedures to develop highly engineered timber products to achieve increased load-bearing capacity and stiffness [1–6]. While steel and concrete are still primarily used for medium to high-rise buildings, recent advances in the development of engineered wood products and connection technology have contributed to a revival in the use of timber in construction with many large scale structures now being produced all over the world [7–13].

Timber is an orthotropic material and while timber has good strength parallel to the grain it demonstrates poorer strength perpendicular to the grain. Stress perpendicular to the longitudinally orientated fibres of the timber can cause the fibres to compress,

which can lead to large deformations. As a result, during the design process, careful consideration is given to timber elements subjected to stress perpendicular to the grain. This is particularly important in areas of support, which are subjected to load concentrations [14,15].

While the calculation of structural compressive design capacity has been widely debated over the past decade [15,16], there has also been increased research activity and engineering advances that have focused on reinforcing timber to increase the compressive capacity perpendicular to the grain. The reinforcement techniques, which are well described in the literature [17–20], allow for the reinforcement of timber perpendicular to the grain using bonded in rods or self-tapping steel 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 method can be quick and easy to install but can also result in the steel being underutilised in terms of stress.

The purpose of this study is to investigate the use of densified wood dowels as a possible sustainable alternative to self-tapping steel screws against compressive stresses perpendicular to the grain. Densified wood used in this study was made by compressing timber under heat and pressure through a process known as thermo-mechanical compression. The primary objective of this process is to enhance the structural properties of the wood by increasing its density. Applying heat to the wood in the range of 120-160°C results in softening of the lignin which enables the compression of the wood cell walls under a compressive load [21–23]. The resulting densified product has been shown to have excellent properties in terms of strength, stiffness and hardness making it suitable for demanding applications [21,24]. Sotayo et al. [21] have shown that increases in strength and stiffness in the region of 100-200% are not uncommon but it should be noted that the results are dependent on species, degree of compression and pressing temperature to name a few of the most influential factors. Mehra et al. [24] demonstrated that densified wood in the form of dowels could even rival steel dowels in a beam-beam spliced connection achieving only 20% less in terms of failure load for comparable designs. The use of densified dowels has recently been examined as a potential method of reinforcement against compressive loads perpendicular to the grain [25] in a similar method currently used with self-tapping screws. A series of studies has also demonstrated the potential to model the complex behaviour of timber elements in structural applications using finite element methods [26–31] including the reinforcement of timber elements with self-tapping screws to help understand the failure behaviour of such reinforced timber elements and aid in the design of safer timber buildings [32–34]. A similar approach is adopted in this study to numerically model the complex behaviour of densified wood dowel reinforced timber subjected to compression perpendicular to the grain. A parametric study is also carried out to examine the influence of the reinforcement geometry on the structural performance.

2. Analytical models and design considerations

2.1. Introduction

While the compression strength parallel to the grain of timber is good, it has been shown that compression perpendicular to the grain requires careful consideration during the design process of timber structures. This section details the analytical equations required to determine the compressive strength perpendicular to the grain of unreinforced and reinforced specimens in accordance with European standards.

2.2. Load Carrying capacity

The compressive strength perpendicular to the grain ($f_{c,90}$) can be determined experimentally and is calculated using Equation (1) in accordance with EN 408 [35].

$$f_{c,90} = \frac{F_{c,90,max}}{bl} \tag{1}$$

where $F_{c,90,max}$ is the maximum force, b is the width of the specimen and l is the length of the specimen. $F_{c,90,max}$ is determined from the nonlinear load-deformation response using the iterative procedure described in EN 408 [35] and illustrated in Figure 1. Initially, an estimate of the maximum compressive force ($F_{c,90,max,est}$) is chosen. An elastic slope (Line 1) is drawn between 10% and 40 % of $F_{c,90,max,est}$ and a parallel line (Line 2) is then offset along the x-axis (displacement) by a value of h_t x 0.01 where h_t is the gauge length. $F_{c,90,max}$ is determined as the point where Line 2 intersects the load-displacement curve. The process should be repeated if $F_{c,90,max}$ is not within a 5% tolerance of the initial estimated maximum compressive force ($F_{c,90,max,est}$). Once the maximum force ($F_{c,90,max}$) is determined, the compressive strength of a timber element perpendicular to the grain can be determined.

2.3. Dowels as Compression Reinforcement

There have been a number of studies that have addressed the used of steel dowels or self-tapping screws as compression reinforcement perpendicular to the grain [17,18,25,33,36,37]. In more recent times, the use of densified wood has been examined in a number of different structural applications, which have shown that densified wood material has increased density, strength, stiffness, hardness and reduced porosity [24]. Typically, it has been shown that as the density of the dowel is increased, there is a proportional improvement in elastic modulus and strength [38,39].

The use of timber or densified wood material has received less attention as a compression reinforcement perpendicular to the grain and while timber has only been examined in a few studies, densified wood has not yet been studied. A study completed by Crocetti et al. [40] on hardwood and steel dowels showed that wooden dowel reinforced specimens significantly outperformed unreinforced specimens and even had better stiffness than steel-reinforced specimens at the early loading stages. However, it was shown that the steel-reinforced specimens ultimately achieved a higher capacity than the hardwood dowel reinforced specimens. Experimental tests conducted by Ed and Hasselqvist [41] has also shown that increases in compressive strength up to 70% can be achieved when using hardwood dowels compared to the
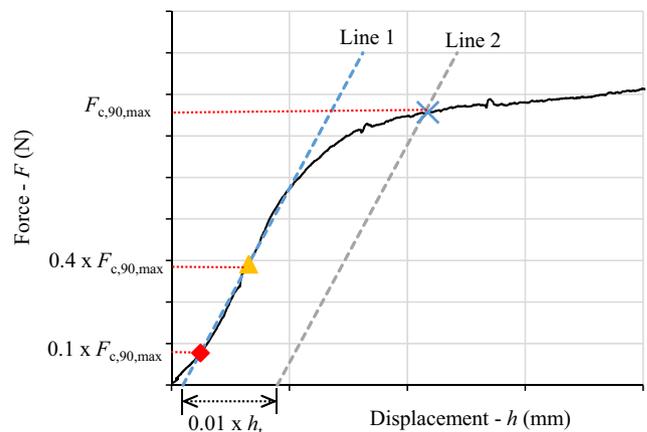

Figure 1. Load-deformation curve analysis in accordance with EN 408 [35]

unreinforced case; however, they did not examine the influence of the dowel length and diameter, which may have a significant effect on the behaviour.

3. Experimental programme

3.1. Introduction

An experimental programme has been designed to investigate the use of compressed wood dowels to reinforce glued laminated elements against compressive force perpendicular to the grain. The experimental test program consists of four series of compression tests. The first test series comprises unreinforced (U) timber specimens, which will form a basis for comparison. The remaining tests are conducted on timber specimens reinforced with densified wood dowels. These are split into three test series with specimens reinforced with two dowels (R2), specimens reinforced with four dowels (R4) and specimens reinforced with six dowels (R6) as shown in Figure 2. The densified wood dowels have a diameter of 10 mm and a length of 100 mm as shown in Figure 2a. The dowel spacing and edge distances are presented in Figure 3. The spacing requirements were based on the dowel diameter (*d*) with 4*d* for the edge distances and 5*d* for the spacing distances in accordance with ETA 11/0030 [42] and Dietsch [36].

3.2. Materials and methods

The densified 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, United Kingdom. The glulam timber specimens used in this study were manufactured using Douglas Fir (*Pseudotsuga menziesii*) grown in Ireland. The density and dynamic modulus of elasticity of each specimen was assessed prior to the manufacture of each glulam specimen. The mean density of the timber was found to be 555 kg/m^3 and the mean dynamic modulus of elasticity parallel to the grain was found to be 11,600 MPa. The cross-section of each specimen measured 160 x 130 mm^2 and the specimen length was 300 mm. 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 within the predrilled holes. This was performed with great care as an uneven distribution of adhesive could contribute to a lack of composite action

between the timber and densified wood dowel and lead to premature failure of the reinforcement scheme. The densified wood dowels were then inserted into the predrilled holes and the adhesive was allowed to cure. The dowels were cut close to the surface of the timber specimen and the surface was sanded to create a smooth loading surface. The preparation of a reinforced specimen is shown in Figure 4.

Each test specimen was subjected to a compression loading procedure in accordance with EN 408 [35]. In order to ensure there is effective stress distribution through the test specimens due to the composite action between the timber and the densified wood dowels [43], it was necessary to increase the dimensions of the test specimen from that specified in EN 408 [35]. The effective loaded length used for verification is a plane defined at the dowel tip as per the design approaches for self-tapping screws presented by Dietsch [36]. The angle of stress distribution is assumed to be 45°– measured from the top of the dowel hence a specimen length of 300 mm was used in this study. A steel plate with a fixed area of 120 x 120 mm^2 was placed centrally on the top surface of each specimen and subjected to a compressive load perpendicular to the grain at a constant cross-head movement to ensure failure was achieved in 300 ± 120s in accordance with EN 408 [35]. The global displacement perpendicular to the grain was measured over the entire height of the specimen using a Linear Variable Displacement Transducer (LVDT) attached to the crosshead of a Denison hydraulic testing machine, model T42B, rated to 500 kN. For a detailed analysis of the experimental results, refer to [25].

4. Numerical modelling of dowel reinforced specimens

The use of finite element (FE) modelling is an effective tool to model complex assemblies in order to predict the structural behaviour and provide a detailed insight into the mechanical response of composite systems. In this section, a full 3-dimensional FE model has been developed to examine the global behaviour and localised stress distribution of unreinforced and reinforced glued laminated timber specimens subjected to compressive loading perpendicular to the grain. The numerical simulations were carried out using the ABAQUS/Explicit software package [44]. The model geometry can be seen in Figure 5. For the purpose of this study, the longitudinal (L) grain direction is aligned with the x-axis, radial (R) direction is aligned with the vertical y-axis and the tangential (T) direction is aligned with the z-axis. The complete geometry
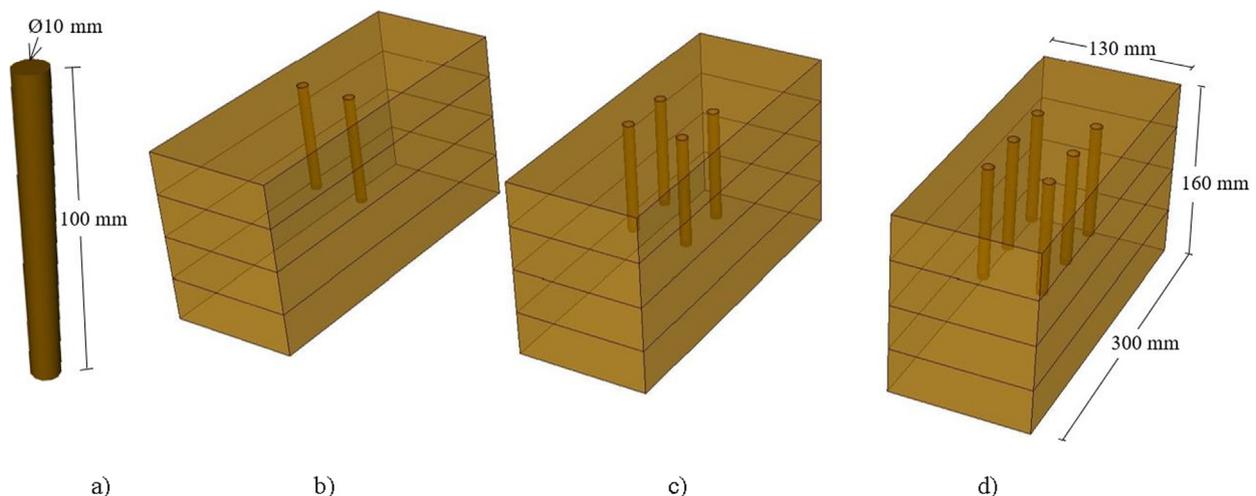

Figure 2. Dowel geometry and test configurations: a) densified wood dowel, b) 2 dowel configuration (R2), c) 4 dowel configuration (R4) and d) the 6 dowel configuration (R6)
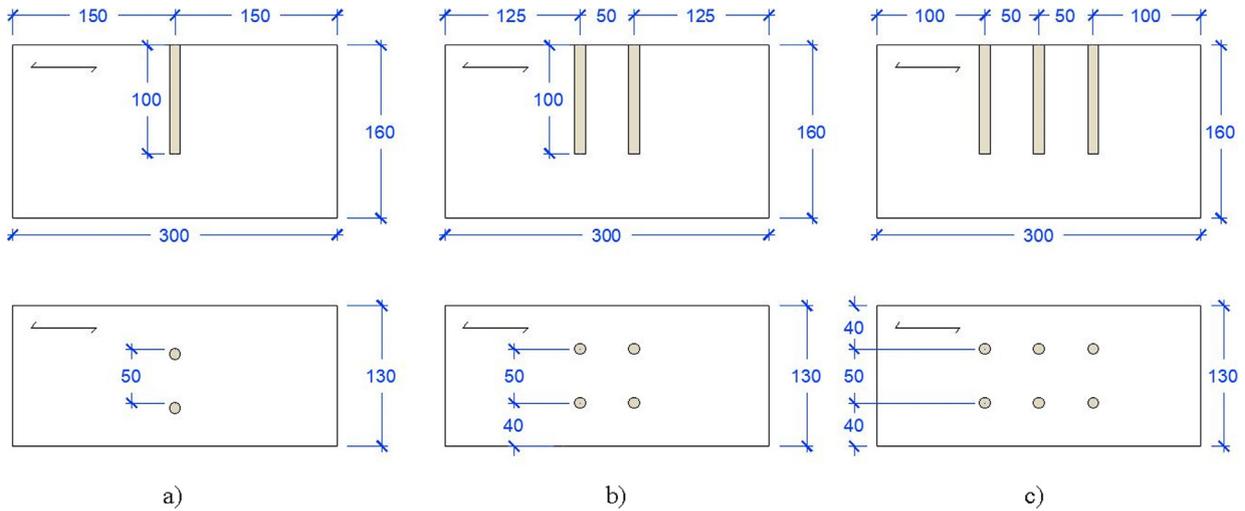
Figure 3. Dowel spacings and edge distances a) 2 dowel configuration (R2), b) 4 dowel configuration (R4) and c) the 6 dowel configuration (R6)
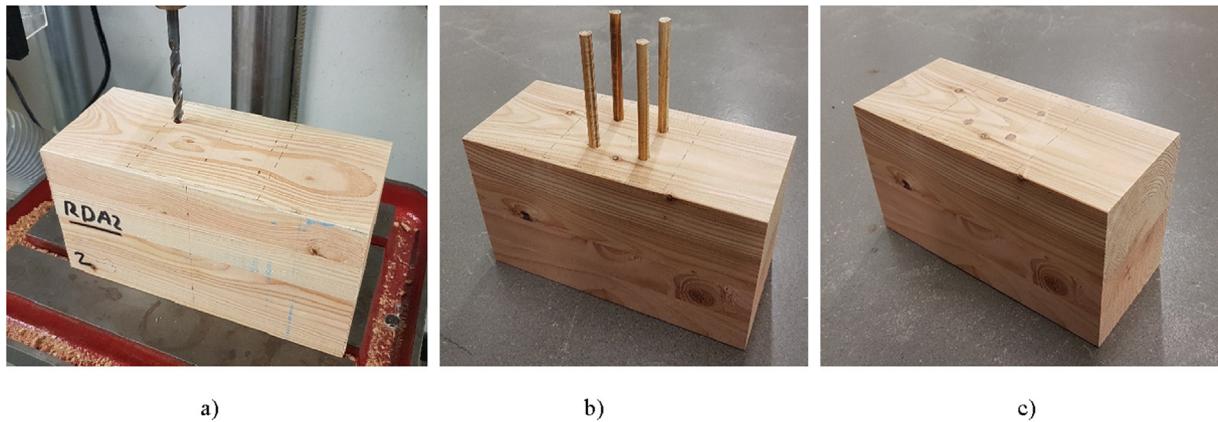

Figure 4. Densified wood dowel reinforced specimen preparation: a) predrilling, b) dowel insertion and adhesive curing, c) excess dowel removed and sanded finish.
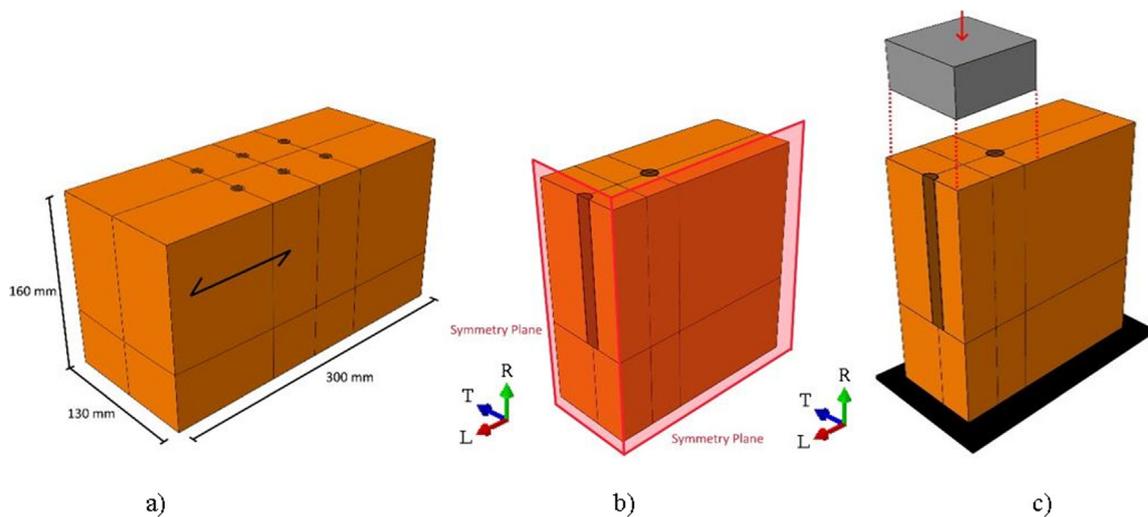

Figure 5. FE geometry: a) complete geometry of 6 dowel configuration (R6), b) 6 dowel configuration utilising quarter (1/4) symmetry, c) steel loading plate application and fixed boundary condition.

can be seen in Figure 5a; however, to reduce the computational time, quarter symmetry was utilised. The planes of symmetry are highlighted in Figure 5b. In Figure 5c, a steel load plate is included,

also taking advantage of quarter symmetry using the appropriate boundary conditions. The top surface of the steel plate in each numerical simulation is subjected to a prescribed displacement

in the vertical radial direction, in order to replicate the displacement-controlled test conditions. The contact interaction between the bottom surface of the steel plate and the top surface of the timber specimen was defined assuming hard contact and a friction coefficient of 0.5 was used for the tangential friction force on the steel-timber contact surfaces [30,45,46]. A similar interaction was also applied to the base of each densified wood dowel in contact with the timber. The base of the timber specimen was fixed in the vertical radial direction as seen in Figure 5c so no vertical deflection can occur in order to replicate the experimental conditions of a fixed base.

For each numerical simulation, the glued laminated timber specimens and the densified wood dowels were modelled as orthotropic, linear elastic materials in tension and linear elastic-plastic materials in compression. The elements were modelled with 8-node hexahedron continuum elements with reduced integration and enhanced hourglass control (C3D8R). The respective mesh sizes for the unreinforced and reinforced models were determined from mesh sensitivity studies to provide accurate results in a reasonable time frame.

Cohesive zone modelling (CZM) has previously been used to great effect to model the complex interaction between timber elements and self-tapping screws, dowel type connection or bonded in rods etc. [32,33,47,48]. In the present study, CZM is incorporated to model the cohesive interaction between the dowel-timber interface. The cohesive interaction aims to account for the possible failure mechanisms at the dowel-timber interface, specifically damage occurring due to shear when subjected to stresses perpendicular to the grain. The initiation of damage of the bonded interface is governed by Equation (2)

$$\max\left\{ \frac{\langle t_n \rangle}{t_n^0}, \frac{t_{s1}}{t_{s1}^0}, \frac{t_{s2}}{t_{s2}^0} \right\} = 1 \tag{2}$$

where t_n^0, t_{s1}^0 and t_{s2}^0, represents the maximum allowable values of stress associated with deformations of the dowel-timber interface in the normal (n), first (s1) and second (s2) shear directions, respectively. A maximum nominal stress of 5 MPa for all directions has been used in this model based on the characteristics of the adhesive used and a linear damage law has been implemented based on the displacement. The linear damage evolution law describes the linear degradation of residual stiffness of the dowel-timber interface with complete damage evolution at the first attainment of 2.5 mm of deformation. This limit was deemed conservative for the application due to a lack of more appropriate input data and the results coincided with the approximate yielding of the load-displacement behaviour from experimental tests [25].

4.1. Material properties

The timber and densified wood materials were modelled as orthotropic materials. The nominal elastic modulus values in the directions parallel (E_L) and perpendicular ($E_{R/T}$) to the grain along with the Poisson's ratios [30] and shear moduli in the three orthotropic directions are shown in Table 1. The values chosen were based on experimental findings and a review of the literature of the elastic modulus perpendicular to the grain for similar species with the assumption of common properties in the radial and tangential directions [30,32,49].

Given the grain direction and loading condition (Figure 4c), the Hill plastic criterion was defined to account for different resistance values along the principal directions of interest for timber. For the Hill plastic law, nominal mean resistance values are given in Table 1. The compressive resistance parallel to the grain (L-axis - Figure 5) was set to $f_{c,0}$ = 37.5 MPa. The other Hill stress ratios were calculated to reproduce the mean compressive strength perpendic-

Table 1
Material properties of timber and densified wood material

Property		Timber	Densified Wood
Elastic Modulus (MPa)	E_L	11600	28000
	E_R	350	2240
	E_T	350	1400
Poisson's Ratio	v_{LR}	0.48	0.48
	v_{LT}	0.30	0.30
	v_{RT}	0.56	0.35
Shear Modulus (MPa)	G_{RL}	385	2000
	G_{TL}	338	1880
	G_{RT}	38.5	200
Yield (MPa)	Parallel	37.5	130
	Perpendicular	5	80

ular to the grain, $f_{c,90}$, of 5 MPa (R- and T-axis) and the mean shear strength, f_v, of 5 MPa for timber (LR, LT and RT planes). Finally, a maximum nominal stress failure criterion was defined for the timber members, to reproduce possible local failure phenomena. This was particularly important for perpendicular to the grain loading for the timber elements in contact with the steel load plate, Once the ultimate resistance was attained a linear damage propagation was considered. The timber mechanical properties were set to degrade linearly with complete damage evolution occurring at the first attainment of a plastic deformation of 3 mm [32]. Due to the lack of more appropriate input or test data on this species, a conservative value of plastic deformation was assumed. The material properties for the densified wood (Table 1) were determined from a series of studies focused on characterising densified wood of different species [21,50,51]. The geometry of the timber specimen, geometry of the steel loading plate and the material properties remained constant for each numerical model developed in this study. The only difference is the number of dowels within each model.

5. FEM Results

The developed model, which incorporates CZM interactions between the timber and densified wood dowels, typically predicted a failure of the reinforced specimen characterised by a combination of yielding and crushing of timber substrate, and damage of the densified wood dowel-timber interface. A comparison between an experimental specimen (R6) and the numerical model is seen in Figure 6. It can be seen that there is significant plastic deformation due to the compressive load under the steel loaded plate on the experimental specimen in Figure 6a in addition to some longitudinal cracks. Figure 6b shows the numerical model displacement contour (in meters). It can be seen that the plastic failure behaviour on the surface of the timber appears to have been relatively accurately predicted by the numerical model in Figure 6b. Additional cracks as seen in Figure 6a were not modelled discretely and were not observed in the numerical model.

To further investigate the internal failure behaviour and interaction between the timber and densified wood dowels, the quarter symmetry model is presented in Figure 7a. The use of symmetry reduced the number of elements required from approximately 360,000 to approximately 90,000 (dependent on the reinforcement configuration) for the entire model and also greatly reduced the computational time. In Figure 7b, the displacement contour map of the loaded specimen is presented and the interaction between the dowel and the timber defined by the CZM approach can be seen. It can be seen towards the bottom of the densified wood dowel that greater displacements occur within the timber material immediately surrounding the densified wood dowels which indicates a positive composite behaviour between the two elements and ultimately results in greater load dispersion throughout the
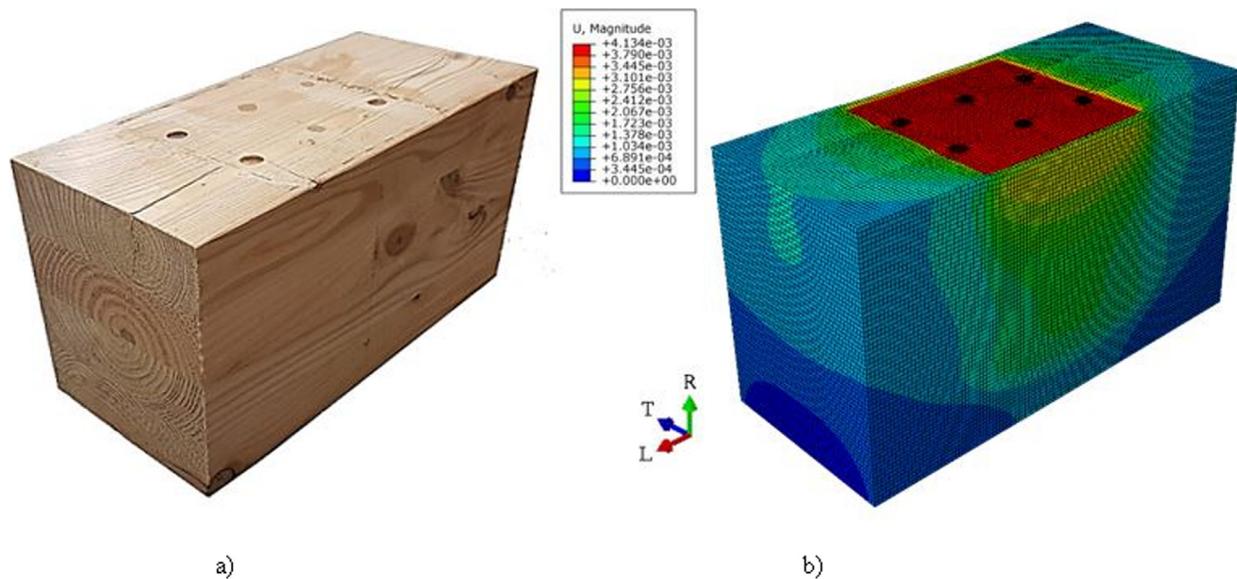
Figure 6. Comparison between a) experimentally tested specimen (R6) with 6 densified wood dowels and b) the displacement (m) contour plot of the numerical model with 6 densified wood dowels (R6).
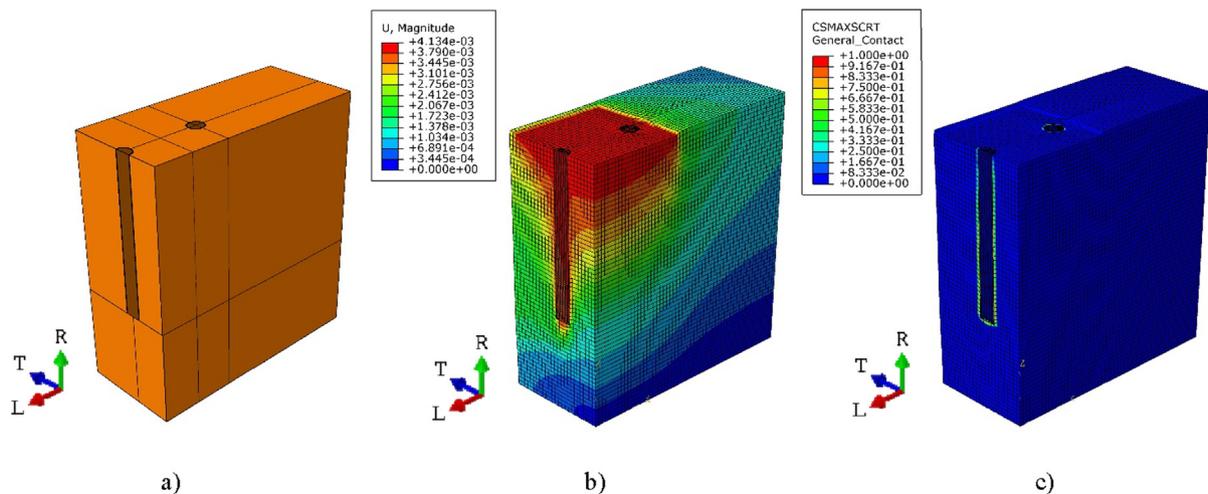

Figure 7. Numerical results: a) model geometry of 6 dowel specimen (R6), b) displacement contour plot (m) at a load of 163.4 kN and c) non-dimensional damage parameter at the dowel-timber interface at a load of 163.4 kN.

timber and greater load-carrying capacity. It is also beneficial to present the non-dimensional 'CSMAXCRT' damage parameter in Figure 7c. This damage parameter ranges in value from 0 to 1 with 0 indicating undamaged and 1 indicating fully damaged interactions of the CZM contact. In Figure 7c, it can be seen that the majority of the CZM interaction is intact but there are areas where the CZM interaction is fully damaged. In all models, it was found that the dowel interaction began to deteriorate towards the bottom of the dowel and progressed upwards towards the top of the dowel as the load increased.

In Figure 8, the load-displacement behaviour of the numerical model is compared to the experimental tests of the four test series (U, R2, R4 and R6). For comparison purposes, the load-displacement behaviour of the numerical model results has been adjusted to account for the initial slip between the steel loading plate timber surface to properly compare the elastic stiffness. This was achieved by adjusting the displacement of the numerical result to coincide with the mean displacement at 10% of the maximum load of the experimental tests. The variation in experimental

test results, which can be seen in Figure 8, is expected and is primarily due to the natural variability in timber and the influence of density on the load-displacement behaviour. While there is a spread within the experimental results due to the natural variability of timber properties, in all cases, the load-displacement behaviour has been relatively well predicted by the numerical model in terms of the elastic stiffness, yield load and plastic behaviour. The numerical model has been shown to predict an increase in elastic stiffness with an increasing number of densified wood dowels which was observed in the experimental tests. Additionally, the model has also observed a delayed initiation of yielding of the composites system with an increased number of densified wood dowels as the load-displacement behaviour transitions from the elastic response to the plastic response. The maximum compressive force ($F_{c,90,max}$) and the corresponding compressive strength of the composite system ($f_{c,90,sys}$) are presented in Table 2 for each test series. The term $f_{c,90,sys}$ is used in this study to represent the compressive strength perpendicular to the grain of the composite system examined in this study to ensure a distinction from the
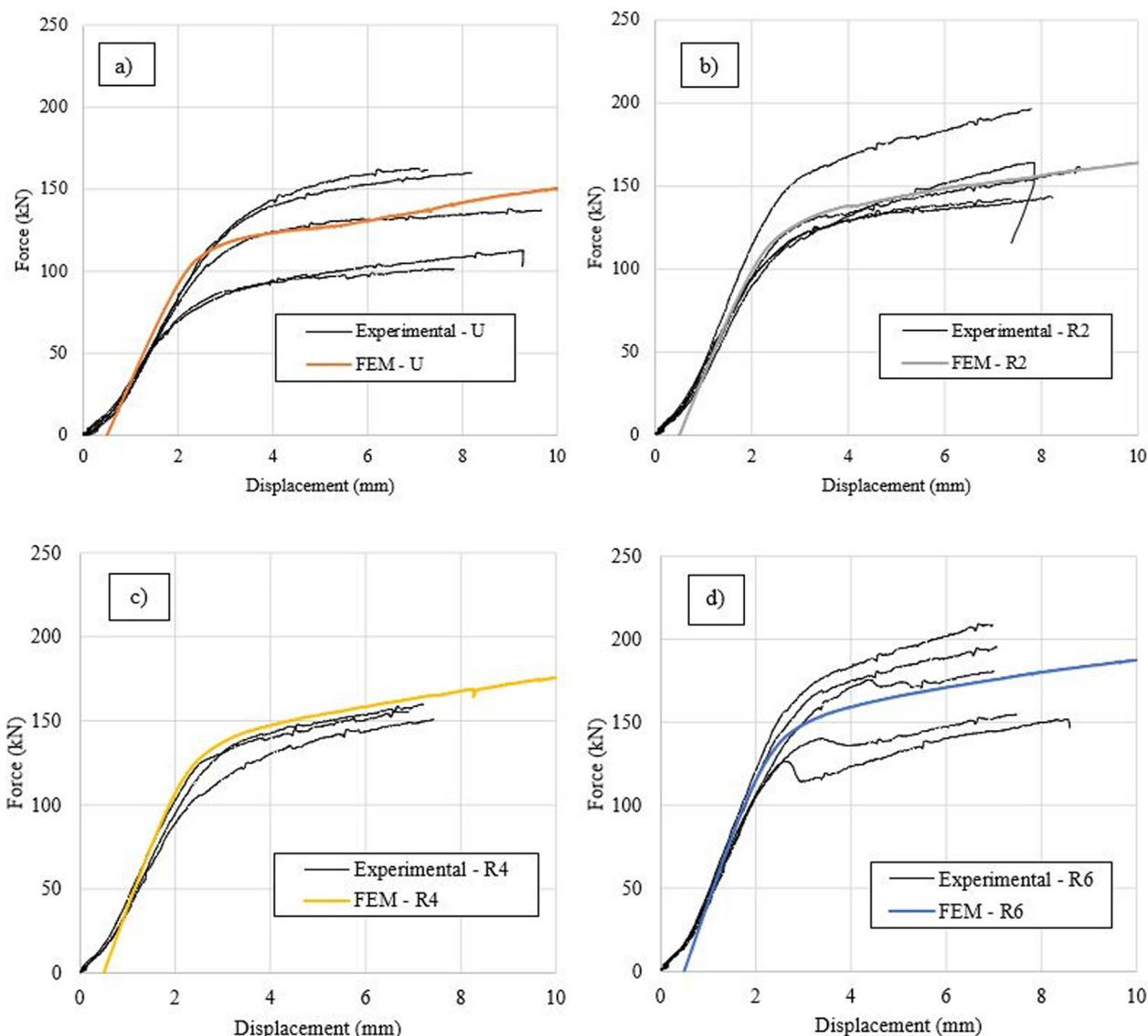
Figure 8. Experimental results compared to the numerical modelled result: a) unreinforced, b) reinforced with 2 densified wood dowels, c) reinforced with 4 densified wood dowels and d) reinforced with 6 densified wood dowels

Table 2
Mean experimental compressive load and strength comparison with numerical models

Configuration	Experimental		Numerical	
	$F_{c,90,max}$ (kN)	$f_{c,90,sys}$ (MPa)	$F_{c,90,max}$ (kN)	$f_{c,90,sys}$ (MPa)
U	124	8.58	123	8.56
R2	143	9.94	138	9.57
R4	141	9.80	147	10.2
R6	161	11.2	159	11.1

material parameter $f_{c,90}$, discussed previously. It can be seen that the addition of reinforcement in the form of densified wood dowels results in an increase in the load-carrying capacity of the timber specimens when compared to the unreinforced series. This trend is also observed for the results of the developed numerical model and there is good agreement between the experimental and numerical results.

For comparison purposes, the load-displacement behaviour of each test series is presented in Figure 9. It is clear to see that the number of dowels can have a significant effect on the load-displacement behaviour. A key requirement of such reinforcement

methods is to increase the load-carrying capacity of timber perpendicular to the grain. It is clear from Figure 9 that with additional dowels, there is an increase in the maximum compressive capacity of the timber elements. There is also an increase in the stiffness of the reinforced timber elements and a delay in the initiation of yielding of the element with increasing dowel numbers. These are important components in the design of timber structures, particularly in areas such as end bearing supports and internal supports. It is also worth noting that, while the number of dowels affects the performance, the influence of dowel diameter and dowel length may also have an important role in the overall
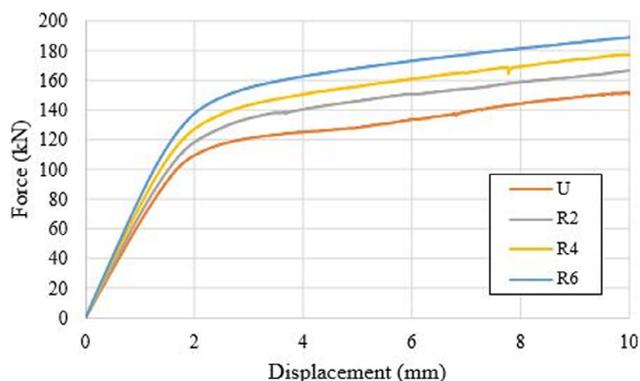
Figure 9. Comparison of numerical modelled results and the influence of the number of dowels on the load-displacement behaviour.

behaviour. The agreement between the experimental and numerical results demonstrates that the numerical model developed herein may be used to further examine the influence of dowel diameter and dowel length in a numerical parametric study.

6. Parametric study

A numerical parametric study has been carried out to examine the influence of dowel length and dowel diameter on the load-carrying capacity of the reinforced timber specimens. The established material properties and the CZM parameters in the developed model have been shown to adequately predict the load-displacement behaviour of timber members reinforced with 2, 4 and 6 densified wood dowels with a diameter of 10 mm and length of 100 mm. Therefore, in this parametric study, the material properties remained the same as previously described in Table 1. The geometry of the timber specimen and particularly the height is an important component when determining the maximum failure capacity ($F_{c,90,max}$) in accordance with EN 408 [35]. In order to focus on the influence of dowel geometry parameters, the geometry of the timber substrate remains constant in this study while the dowel diameter and dowel length are varied. The timber geometry is set at 200 mm in width, 350 mm in height and 500 mm in length. The width of the specimen is based on the spacing and edge distance requirements of the largest dowel diameter and the height and length are based on the longest dowel length. As seen in Figure 9, quarter symmetry is utilised to reduce the computational time of the model and a single densified wood dowel is positioned in the centre of the loaded area. In Figure 10, a 15 mm dowel is

shown with five different dowel lengths, namely, 100 mm, 150 mm, 200 mm, 250 mm and 300 mm. A 3-dimensional numerical model was developed for each dowel diameter and dowel length utilising the CZM approach presented and the maximum compression force ($F_{c,90,max}$) and corresponding compressive strength perpendicular to the grain of the composite system ($f_{c,90,sys}$) were calculated for each condition.

The maximum compression force ($F_{c,90,max}$) results are presented in Figure 10. The result for the unreinforced specimen remains constant regardless of dowel length and serves as a basis for comparison. With increasing dowel length, there is a corresponding increase in the maximum compression force observed. It can also be seen that for each dowel length, an increase in the diameter of the densified wood dowel has a positive influence on the overall compressive resistance of the element.

The perpendicular to the grain compressive strength values of the parametric study are tabulated in Table 3 and graphically presented in Figure 11. There is an improvement in the compressive strength for all specimens when compared to the unreinforced model, which had a compressive strength of 12.73 N/mm². For each dowel length studied, there is an increase in the compressive strength with increasing dowel diameter. This is as expected as with increasing dowel diameter, there is greater contact area/interaction between the dowel and the surface of the timber. The results also indicate that there is an increase in the compressive strength with increasing dowel length, however, with increasing dowel length, the compressive strength eventually begins to plateau with no further increase in compressive strength being observed. To examine this further, Figure 12 shows the percentage increase in compression strength when compared to unreinforced specimens for different dowel diameters and the influence of dowel length.

In Figure 13, it can be seen in that the influence of the dowel diameter has a significant influence on the effectiveness of the reinforcement scheme. The results have shown that for the geometry and loaded area studied, a single 10 mm dowel achieves a maximum percentage increase of approximately 5.0% when compared to the unreinforced sample. The results also indicate that the 10 mm dowel achieves a percentage increase of 5.0% with a dowel length of 200 mm with no further increase in capacity with increased dowel lengths. The 15 mm dowel shows a maximum percentage increase in compression strength of approximately 13% which begins to plateau at a dowel length of between 200 mm and 250 mm. A similar result is seen for the 20 mm diameter dowel which achieves its maximum percentage increase in compression strength capacity of 20.6% at a dowel length of 300 mm. The results would indicate that the compression strength increases as the dowel length-to-diameter ratio approaches 15 and increased
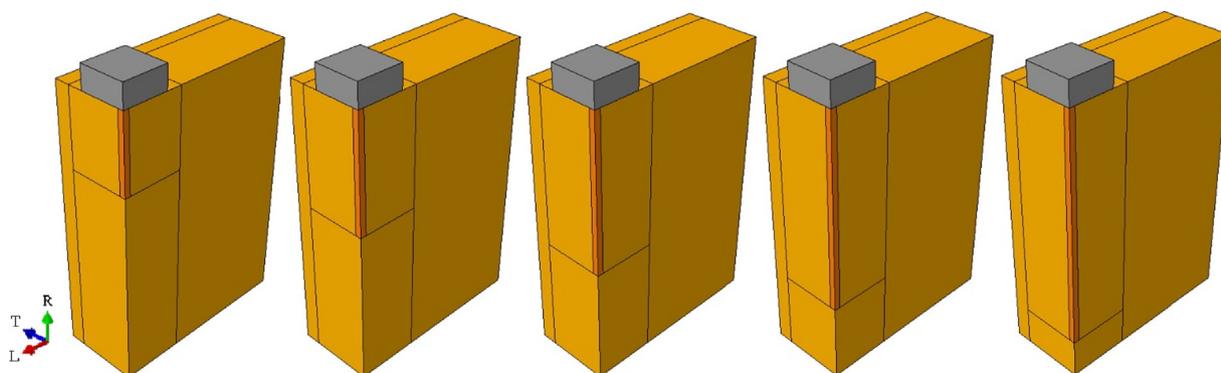

Figure 10. The 3-dimensional geometry generated in ABAQUS (quarter symmetry utilised). The timber and steel loading plate geometry remained constant while the dowel diameter and dowel length were varied. Dowel diameters of 10 mm, 15mm (shown in this figure) and 20 mm were examined, and dowel lengths of 100 mm, 150 mm, 200 mm, 250 mm, and 300 mm were examined.

Table 3

Compression strength perpendicular to the grain ($f_{c,90,sys}$) results from the parametric study

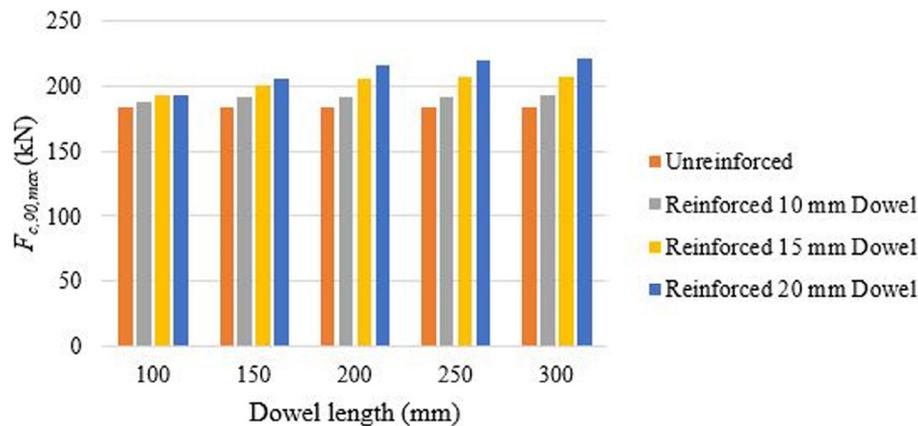| $f_{c,90,sys}$(MPa)	Dowel length (mm)				
	100	150	200	250	300
Unreinforced	12.73	12.73	12.73	12.73	12.73
10 mm Dowel	13.07	13.26	13.33	13.34	13.36
15 mm Dowel	13.36	13.97	14.25	14.34	14.34
20 mm Dowel	13.40	14.31	15.01	15.28	15.35

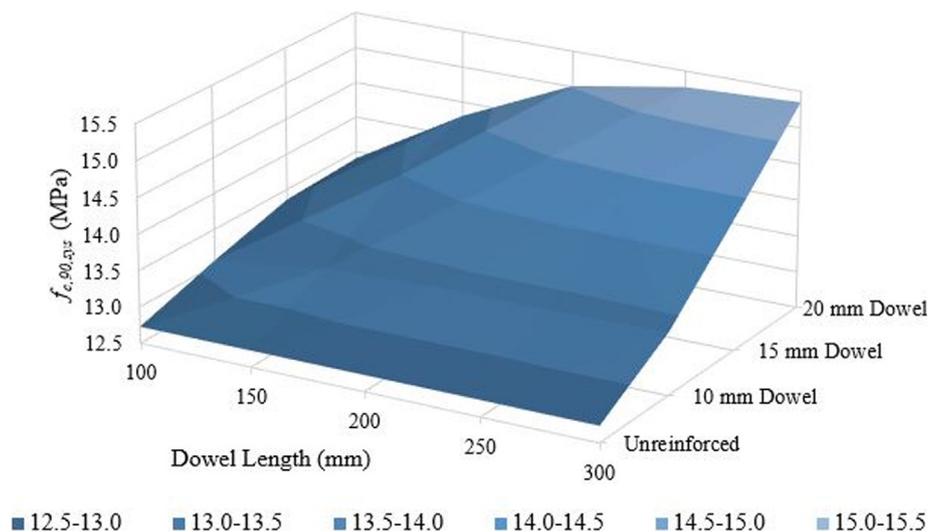**Figure 11.** Maximum compression force ($F_{c,90,max}$) determined in accordance with EN 408 [35].

Figure 12. Surface chart representing the influence of the dowel diameter and dowel length on the compressive strength perpendicular to the grain

dowel lengths beyond this ratio will not result in increased capacity and will be underutilised. Interestingly, similar length-to-diameter ratio limits were found experimentally for glued-in rods bonded perpendicular to the grain under axial tension loads [52]. Further experimental tests are required to validate these findings. The group effect of a number of dowels working simultaneously may also have a significant effect on compressive failure and requires further investigation.

7. Summary and conclusions

A numerical investigation of timber specimens reinforced against perpendicular to the grain loads with densified wood dowels has been carried out. A 3-dimensional solid finite element model has been implemented in ABAQUS/Explicit software. The numerical model utilises cohesive zone modelling (CZM) and Hill plastic yield

criterion to predict the failure behaviour of specimens reinforced with densified wood dowels. The numerical model has been shown to reliably predict the load-displacement response of experimental tests carried out on a total of four test series (unreinforced, reinforced with 2, 4 and 6 densified wood dowels). The developed numerical modelling approach has predicted the behaviour observed experimentally reasonably well. In all models, the crushing of fibres and plastic deformation that was observed experimentally due to the compressive load was predicted by the numerical model, but the model also presents an insight into the mechanical response and local failure of the dowel-timber interface of the composite system. The model has shown that for the material properties presented, the local failure of the dowel-timber interface, which could not be observed experimentally, began near the bottom of the dowel and progressed upwards towards the top of the dowel as the load increased. Additionally, some yielding of the dowel was observed at higher loads. The validated model was
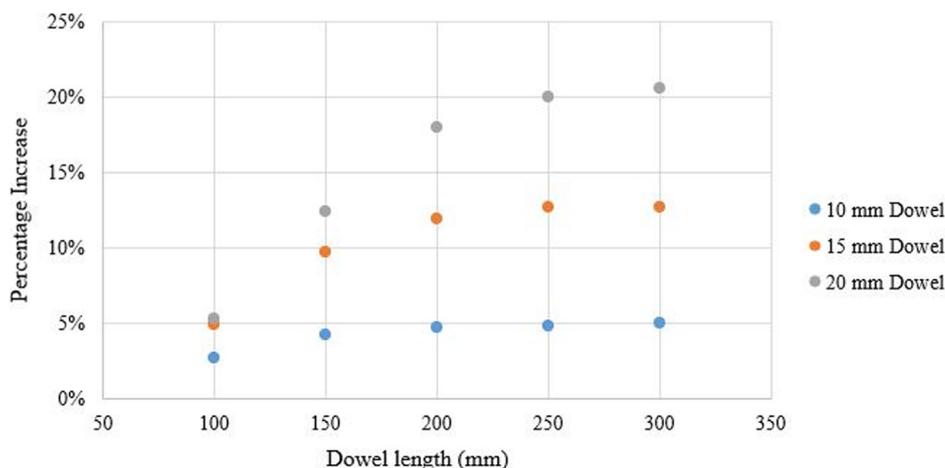
Figure 13. Percentage increase in compression strength when compared to unreinforced specimens and the influenced of dowel diameter and length.

then used in a parametric study to examine the influence of densified wood dowel diameter and dowel length on the capacity of timber elements against compressive loading perpendicular to the grain. The validated numerical model has the capability to be used to further examine different reinforcement scenarios and geometries for practical applications of this technology.

The following conclusions can be formulated based on the finite element study utilising a 3-dimensional solid finite element model to examine the use of densified wood as a suitable reinforcement for timber elements against compression loading perpendicular to the grain.

- The developed numerical model incorporating CZM has been validated against experimental tests results and has been shown to reliably predict the enhancement in compressive strength and stiffness of timber members reinforced perpendicular to the grain with densified wood dowels.
- The validated model provides a useful tool for further investigation of different reinforcement schemes using this technology and has been used to perform a parametric study to examine the influence of densified wood dowel diameter and length on the compressive strength perpendicular to the grain. The numerical results indicate that there is an increase in the compressive strength with increasing dowel diameter and there is an increase in the compressive strength with increasing dowel length; however, there appears to be a limit beyond which increasing the dowel length has limited influence.
- An upper limit of dowel length-to-dowel diameter of 15 has been observed for the test geometry and loaded area examined in this study. Increasing the dowel length-diameter ratio beyond a value of 15 resulted in an underutilised dowel and it did not result in a further increase in capacity.

Further studies are required to firstly, experimentally confirm the findings from the parametric study presented herein and secondly, to utilise the developed modelling approach to further examine the influence of dowel length and dowel diameter on multi-dowel reinforcement configurations to observe the behaviour of a group of dowels working simultaneously.

CRediT authorship contribution statement

C.O.C. contributed to the conceptualization, methodology, experimental investigation, supervision and data analysis of the project in addition to writing, reviewing and editing of the final article. M.C. was involved in the experimental activities data analysis and writing, reviewing and editing of the final article. S.M contributed to the conceptualization, experimental investigation and reviewing and editing of the final article. A.M.H. was involved in the acquisition of funding for this project, supervision of all experimental activities and writing, reviewing and editing of the final article.

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