

Mechanical behaviour and 3D stress analysis of multi-layered wooden beams made with welded-through wood dowels.

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Abstract:

This paper presents novel full-scale timber multi-layered beams using welded-through wood dowels in place of metallic fasteners, connectors, and the traditional poly(vinyl acetate) (PVAc)-adhesives. Two meter timber four-layer beams are constructed in this fashion with variation of the number of dowels in each. Four-points bending tests were carried out to evaluate to mechanical performances of such beam systems. The practical difficulties encountered in constructing deeper multi-layer beams are discussed and possible solutions which have been employed for the purpose of this work and proved successful are presented. In order to investigate thoroughly the full potential of multi-layered beams with a very limited number of experimental studies, a 3D FE model has been presented, validated against experimental results and then used to study some influential parameters. The results showed that a reasonable bending stiffness of multi-layered beams is achievable with a good combination of material and geometric parameters.

Keywords: Welding/Joining, Layered Structures, Wood, Finite Element Analysis (FEA), Modelling

1. Introduction

Glulam is extensively used in the timber construction industry in many European countries since the end of the 19th century due to its efficiency and variety of shapes. Glulam beams are made of wood laminations glued together, using different adhesives, to form a specific piece of wood for a specific load [1]. Mechanical performances of glulam have been

studied for more than 50 years. Experimental and numerical investigations were continued until today to provide thorough understanding of such beam systems. Some studies have focussed on the different types of solutions used to strengthen glulam [1–4]. Other researchers [5], among others, have studied the effect of density and production parameters on bending strength of glulam.

In recent years, research on wood dowels for structural timber joining has greatly increased due to their cost and positive environmental impact. Obtaining a good compatibility of joint systems is another major advantage of wood dowels against steel fasteners [6]. Pizzi *et al.* [7], Vaziri *et al.* [8] and Kanazawa *et al.* [9], among others, studied the performance of timber assemblies made with welded wood dowels as a connecting elements replacing traditional poly(vinyl acetate) (PVAc)-glued dowels and nailing. The mechanical behaviour of welded dowels was obtained by shearing tests showing rapidly yield considerable strength for welded wood dowel assemblies. Guan *et al.* [6] and Jung *et al.* [10] have studied timber joint systems using compressed wood fasteners and plates in place of steel fasteners. Tests have been made on different types of beam-to-column connections. In these tests, pull out strength and moment-rotation relationship were studied. Hassel *et al.* [11] have investigated the performance of a wooden block shear wall assembled with compressed wood dowels. Bocquet *et al.* [12] undertook studies on small-scale and full-scale two-layer timber beams joined with welded wood dowels. The relation between the applied load and deflection as well as the load carrying capacity of two-layer timber beams was measured and compared to that obtained with nailing and glued dowels. The results showed clearly the role of the wood dowels in absorbing shear stresses.

More recently, experimental tests have been made on full-scale welded-wood dowel four-layered beams, at the School of Architecture, Landscape and Civil Engineering of the University College of Dublin. In general, measurements in these tests include: the relation between load and deflexion, and stiffness of beams to evaluate the bending behaviour. The obtained results have shown the significant promise of such layered beam systems and their development is of particular interest for the timber construction industry. In fact, this can find extensive applications by replacing the traditional poly(vinyl acetate) (PVAc)-adhesive, contained in traditionally produced glulam, which leads to problems of real, potential or perceived pollution, as well as problems of deposits on the adhesive-applicators and of cleaning which are in general costly. Other major advantages to use wood dowels against traditional poly (vinyl acetate) (PVAc)-adhesive are the reduction of CO₂ and COV, and better recycle ability, because they are made with only naturally renewable material.

However, if the strength characteristics of wood-dowel layered beams are stronger in the longitudinal direction, their low bending strength (in the transverse direction) when compared to traditionally produced glulam and equivalent size solid wood, can limit their applications. Furthermore, there is still a need for insight knowledge of the potential trial of these beam systems. The strength of wood doweled multi-layered beam has to be enhanced to bending stiffness (or strength). As documented in [5], this bending strength is closely related to some material and geometric parameters. Thus, one wishes to investigate the effect of some parameters, such as mechanical properties of dowels and layers, thickness of timber assembled layers, diameter of dowels (or number of row of dowels), which have more or less significant role on the strength of multi-layered beams. In addition to experimental study, the numerical simulation is used to obtain information inaccessible with experiments, anyhow without very expensive experiments and hugely time consuming.

After presenting the experimental work undertaken to construct the wood dowel four-layer beams, this paper describes a finite element based model which was validated against the results of an experimental test on a typical wood-dowel four-layered beam and then used to cover some variations of wood-dowel four-layered beam design. Orthotropic elastic and elasto-plastic constitutive laws [13-16] have been used to model the wood dowels and layers in tension and compression, respectively.

Simulation results demonstrate clearly how mechanical performance of wood-dowel layered beams can be improved by combining appropriate material and geometric parameters. Such beam systems needs, however, to be more investigated to unlock their full potential.

2. Experimental

2.1. Construction of four-layer beams

In this study, C16 Irish Spruce was used to construct the four-layered beams. The layer dimensions were 140 x 38 x 2200 (mm). Commercially fluted beech dowels of 10 mm of diameter and 200 mm long were used for the assemblage of layers. All four-layered beam systems had equal layer thickness and only one row of wood dowels with same diameter inserted at 60° with respect to the plane of the substrate surface. Note that when insertion of the 200 mm dowels began in the four-layer beams, splintering at the base of the dowel reappeared. This complication by splintering was observed when the dowels passed a depth of two layers, due to the increase of the introduction force of dowels. One option which leads to avoid splintering of dowels is the increase of the diameter of the hole of layers, further, that would reduce the required introduction force of dowels. However, this option is ineffective as the dowel was able to pass quite freely through the hole. In fact, little or no friction existed between the dowel and substrate resulting in not enough heat being generated during the weld

process to cause melting of the lignin nor enough mechanical resistance to aid entanglement. Another option would be the use of plasticising compounds, such as water, petroleum jelly, vegetable oil, and sunflower oil [9]. Sunflower oil was chosen as the plasticiser to use as its affects on the tensile capacity of the joint, although slightly negative, had been documented in previous research [9]. To try and achieve the same affect on the weld the dowels were soaked for ten minutes in sunflower oil to a depth of 160 mm. The top 40 mm was not soaked for two reasons, it was not entering into the layers and it was being held in the drill and so the sunflower oil would have hampered the drills grip on the dowel. It was also gleaned that adjusting the rate on of dowel introduction on a dowel-by-dowel basis as lead to an increase in the number of successful insertions.

Finally, with this construction process proving successful, a total of seven four-layer beams were constructed (Fig. 1). The number of dowels in each beam was varied in order to determine their effect on the stiffness of the beam. Two beams were made with 56, 44, and 32 dowels and one final beam with 20 dowels. Note that this study constitutes a good contribution, since the layered beams are welded at much greater depths than previously achieved [12]: this increase in depth from 76 mm to 152 mm.



Fig. 1: 20-dowel four-layer beam held in clamps during construction

2.2. Four point bending tests and results

All four- layered beam systems were loaded in four-point bending tests up to 7.22 kN, with test arrangement as shown in Fig. 2. The load was applied using an Instron 8500 series load cell. A steel jig consisting of two 80 mm and 90 mm box sections and two half cylindrical load pads were used to convert the one point load of the Instron load cell to two point loads acting on the beam.

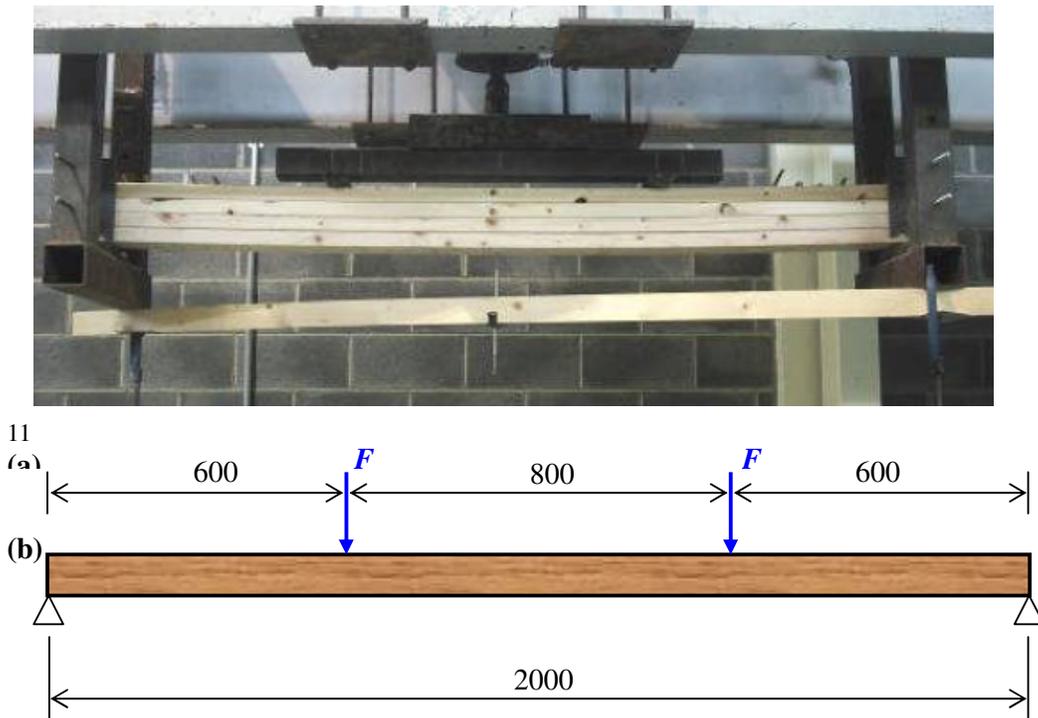


Fig. 2: Four-point bending tests: (a) four- layer beam during test, (b) test arrangement (in mm)

Fig. 3 shows typical load–deflection curves for layered beams made with different number of dowels: 20, 32, 44 and 56. It can be seen that both the 56-dowel and 44-dowel beams appeared to be of similar stiffness as do the 32-dowel beam. The 56 and 44-dowel beams are of a greater stiffness than the other set of beams.

Note that the lower stiffness was obtained for the 20-dowel beam by comparison with the other doweled beams and that while stiffness increases with increasing number of dowels

over a certain level an improvement decreases until it ceases all together. Thus, there is practically no difference between the 56 and 44-dowel beams.

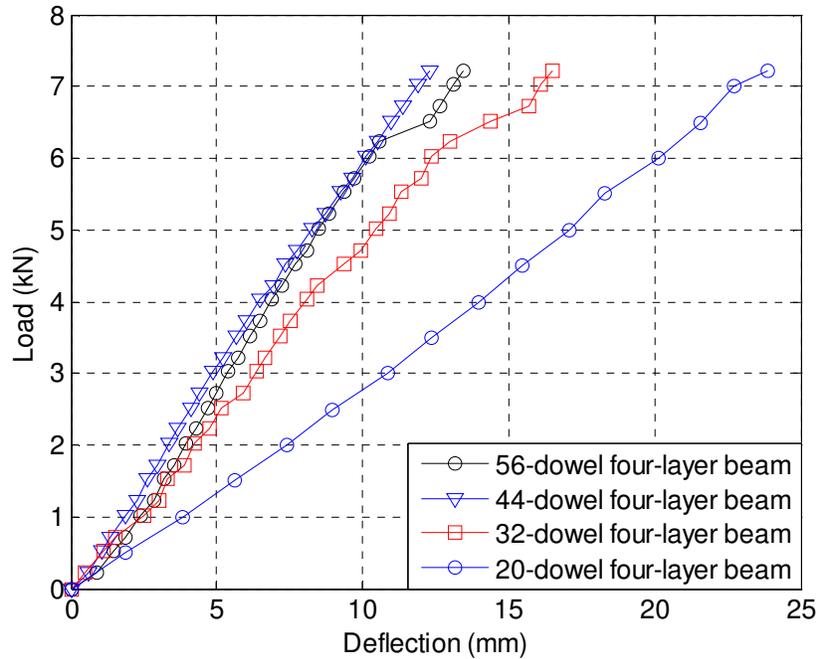


Fig. 3: Experimental load–deflection curves of a four-layer beam as a function of number of dowels

3. Numerical modelling

This section presents a 3D FE-model as an attempt to simulate the structural response of the doweled multi-layered beams. Once the FE-model is verified against experiments, parametric study can be undertaken towards the improvement of the design of multi-layered beam systems, with limited number of measurements and structural tests. In this study, we limit ourselves to deal with the 56-dowel four-layer beam (Fig. 4), where the dowels 1 to 10 and dowels 11 to 28 are called dowel groups 1 and 2, respectively.

The timber density was 420 kg/m³ and the moisture content was around 12%. The timber used in this study was Irish spruce wood. Its density was 420 kg/m³ and the moisture content was around 12%. Material properties are: $E_1 = 12.9$ GPa, $E_2 = E_3 = 0.43$

GPa, $\nu_{12} = \nu_{13} = 0.3$, $\nu_{21} = \nu_{31} = 0.01$, $\sigma_c = 6$ MPa.

In the last decade, constitutive modelling of timber material, using the finite element method, has increasingly been used as a development and analysis tool in a large number of research laboratories. The analysis of non-linear behaviour of timber has been studied by many authors using 2D or 3D approaches. In particular, the most 3D F.E. models dealing with the plastic yielding of timber material that can be found in the literature are based on the Hill's criterion, among others. The Hill's criterion is the generalized form of the von Mises criterion and has been shown to accurately describe the anisotropy of materials.

In this study, the timber was modelled as elasto-plastic orthotropic material with non-linear hardening associated with material densification, without distinction between radial and tangential properties. The anisotropic flow was described using the quadratic Hill's criterion, which can be expressed as follows:

$$2 f (\sigma_{i j}) = F (\sigma_y - \sigma_z)^2 + G (\sigma_z - \sigma_x)^2 + H (\sigma_x - \sigma_y)^2 + 2 L \sigma_{yz}^2 + 2 M \sigma_{zx}^2 + 2 N \sigma_{xy}^2 = 1 \quad (1)$$

where:

F, G, H, L, M and N are the six anisotropic constants which should be determined by tests on the material in different orientations.

The modelling approach is based on the thermodynamic approach of irreversible processes with internal variables developed in the context of large deformation theory for the three-dimensional continuum.

The state variables are given hereafter as follows:

$$\underline{\hat{\sigma}} = (1 - k) \underline{\sigma} = (1 - k) \underline{\underline{\Lambda}} : \underline{\underline{\varepsilon}}^e \quad (2)$$

$$\underline{\hat{R}} = \underline{Q}r \quad (3)$$

$$Y = \frac{1}{2} \underline{\underline{\varepsilon}}^e : \underline{\underline{\Lambda}} : \underline{\underline{\varepsilon}}^e \quad (4)$$

where:

$\underline{\underline{\hat{\sigma}}}$ is the second order effective stress tensor, $\underline{\underline{\varepsilon}}^e$ denotes the second order tensor of elastic strain, $\underline{\underline{\sigma}}$ is the Cauchy stress, R and r represent the isotropic hardening and the isotropic strain respectively, k the densification parameter, Y is the energy restitution rate, Q is the isotropic hardening parameter, $\underline{\underline{\Lambda}}$ is the fourth order orthotropic elastic matrix.

The mechanical dissipation is described with one potential $F(\underline{\underline{\hat{\sigma}}}, R; k)$, which controls the plastic flow $f(\underline{\underline{\hat{\sigma}}}, R; k)$, and the evolution of the densification k , with one plastic multiplier $\dot{\lambda}$.

$$f(\underline{\underline{\hat{\sigma}}}, R; k) = \|\underline{\underline{\hat{\sigma}}}_{eq}\| - R - \sigma_c = 0 \quad (5)$$

$$\text{with } \|\underline{\underline{\hat{\sigma}}}_{eq}\| = \sqrt{\underline{\underline{\hat{\sigma}}} : \underline{\underline{H}} : \underline{\underline{\hat{\sigma}}}}$$

$$F(\underline{\underline{\hat{\sigma}}}, R; k) = f + \frac{1}{2} \frac{b}{Q} R^2 + \frac{S}{(s+1)} \left(\frac{Y}{S} \right)^{s+1} \quad (6)$$

where:

$\|\underline{\underline{\hat{\sigma}}}_{eq}\|$ and σ_c are the equivalent stress and the yield compressive stress, respectively, Q and b are the material parameters which characterize the isotropic hardening, S and s characterises the densification evolution, $\underline{\underline{H}}$ defines the Hill's fourth order plastic anisotropy.

Based on the normality rule, the relationships associated with the internal variables (Eq. 2 to Eq. 4) can be expressed as follows:

$$\underline{\underline{\dot{\varepsilon}}}^p = \dot{\lambda} \frac{\partial f}{\partial \underline{\underline{\hat{\sigma}}}} = \dot{\lambda} \frac{\underline{\underline{H}} : \underline{\underline{\hat{\sigma}}}}{\|\underline{\underline{\hat{\sigma}}}_{eq}\|} = \dot{\lambda} \underline{\underline{n}} \quad (7)$$

$$\dot{r} = \dot{\lambda} [1 - br] \quad (8)$$

$$\dot{\mathbf{k}} = \dot{\lambda} \begin{bmatrix} \mathbf{Y} \\ \mathbf{S} \end{bmatrix}^s \quad (9)$$

where:

$\underline{\epsilon}^p$ is the plastic strain rate tensor, $\dot{\lambda}$ is the plastic multiplier which is obtained from the consistency condition ($f = \dot{f} = 0$), \underline{n} is the outward normal to the yield surface with densification effect defined in the stress space, \dot{r} is the isotropic hardening strain rate and \dot{k} is the densification rate.

Particular attention was made for the tension behaviour. In fact, the behaviour of timber in tension is brittle, while in compression perpendicular to the grain, the timber exhibits plasticity and can thus be accurately modelled by an elasto-plastic law with hardening. In order to take into account the difference in strength between tension and compression, a brittle failure criterion, that has been largely used for anisotropic materials, was adopted (Eq. 10): it states that the material will fail when any one of the stresses in the principal material directions exceeds the material strength in that direction.

$$\begin{aligned} & a_1(\sigma_y - \sigma_z)^2 + a_2(\sigma_z - \sigma_x)^2 + a_3(\sigma_x - \sigma_y)^2 + a_4\sigma_x \\ & a_5\sigma_y + a_6\sigma_z + a_7\tau_{yz}^2 + a_8\tau_{xz}^2 + a_9\tau_{xy}^2 = 1 \end{aligned} \quad (10)$$

with:

$$\begin{aligned} a_1 &= \frac{1}{f_{t,90}f_{c,90}} - \frac{1}{2f_{t,0}f_{c,0}}; & a_2 &= a_3 = \frac{1}{2f_{t,0}f_{c,0}}; & a_4 &= \frac{1}{f_{t,0}} - \frac{1}{f_{c,0}} \\ a_5 &= a_6 = \frac{1}{f_{t,90}} - \frac{1}{f_{c,90}}; & a_7 &= a_8 = a_9 = \frac{1}{f_v^2} \end{aligned}$$

where: $f_{t,0}$ and $f_{t,90}$ are the tensile strengths parallel and perpendicular to the grain, $f_{c,0}$ and $f_{c,90}$ are the compressive strengths parallel and perpendicular to the grain, and f_v is the shear strength.

The above constitutive model is successfully implemented in the commercial ABAQUS software. For a better reading about the numerical aspects and the implementation procedure, the reader is referred to [13, 14].

By considering the two plans of symmetry, only one quarter of the four-layer beam was modelled, involving two types of external boundary conditions: those due to symmetry (for both the layers and dowels) and supports, and those due to loading. The load was introduced by imposing controlled displacement according to the arrangement shown in Fig. 2b.

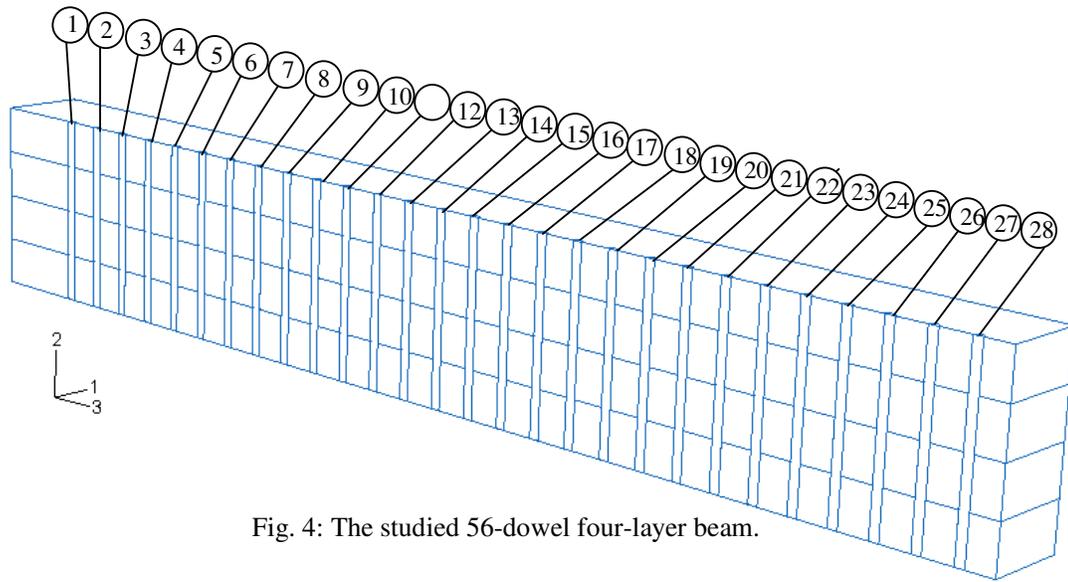


Fig. 4: The studied 56-dowel four-layer beam.

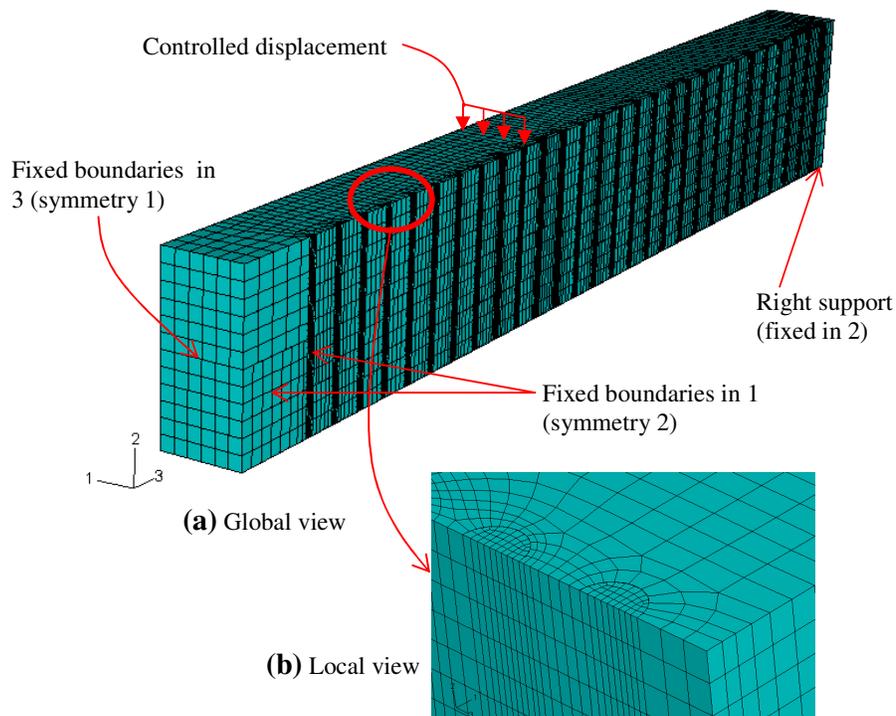


Fig. 5: Mesh generation for one quarter of the 56-dowel four-layer beam with loading and boundary conditions.

The layers and dowels were meshed using 8-node hexahedral elements. Fig. 5 shows typical mesh generation for a four-layer beam including loading and boundary conditions. Since there was expected to be high deformation in the area of the dowels where the four layers move in opposite directions, relatively fine meshes were used in these zones.

In this type of layered beams, contact between the layers and the dowels inserted at 60° , with respect to the plane of the substrate surface, act in addition to the highly anisotropic behaviour of the timber leading to severe complicating features in the FE-analysis. In fact when dowels are inserted at an angle which is different than 90° , it would be necessary to use hundreds of thousands or even smaller tetrahedral elements in the FE-model, involving unacceptable extensive computing times. As a first assumption for this study, the real dowel inserted at 60° has been replaced by a fictitious dowel inserted at 90° , and considering its local material orientation turned (swivelled) by 60° , to take into account the oblique properties of real dowels (Fig. 5).

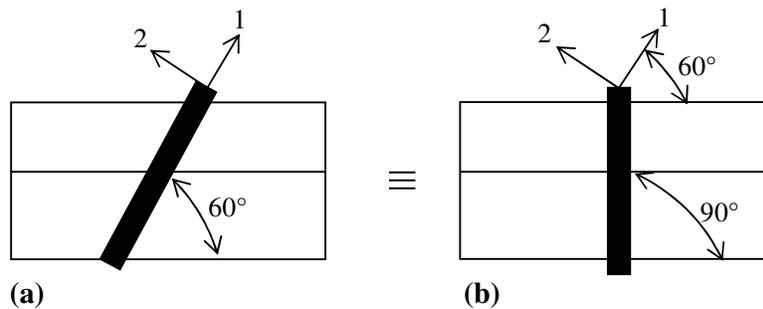


Fig. 5: Assumption adopted for the FE model: (a) real dowel, (b) fictitious dowel

The contact between the layer interfaces is based on the master–slave contact approach. The Coulomb traction model was adopted with friction ratio $\mu = 0.18$ and the interaction between layers is formulated using the finite sliding approach, which allows the separation of the two surfaces during sliding.

The weld at the dowel/hole interfaces was not modelled in details but each interface between the holes and the dowels is clearly identified in the 3D FE-model. Detailed F.E modelling and analysis are difficult and beyond the scope of the present study which aims more to have a global understanding of the problems involved in the analysis and design of doweled multi-layered beams.

Since there is no damage model, at this stage of the study, to simulate progressive failure of the weld, the behaviour at the dowel/hole interfaces has not however been forgotten with different simplification assumptions, involving two numerical models:

- (i) Model 1: the nodes at the interfaces belonging to the dowels and holes are tied leading in fact to a continuous medium. This assumption has been used by many authors to good effect [3, 17, 18];
- (ii) Model 2: assumption of contact with friction at the dowel/hole interfaces.

In the model 1, the layer holes are well bonded to the dowels, in comparison to the real yield strength of the weld. Such tied regions of stiff nature imparts relatively high stiffness to the whole model of the two-layer beam, thus the stiffness of the beam would be slightly overestimated. In model 2, however, the friction coefficient at the dowel/hole interfaces would play an important role on the global behaviour of the beam system and the use of lower friction coefficient would lead to under-estimate the behaviour of the beam system. In the finite element model as finally developed, the friction coefficient has been adjusted and a high friction coefficient was used and was found to improve the simulation results greatly.

The numerically predicted load–deflection curves are plotted for both the model 1 and model 2 against the corresponding experimental result, which are shown in Fig. 6. A fairly good correlation is obtained with model 2, when using a higher friction coefficient of

$\mu = 0.6$. It can be observed that the numerically predicted load–deflection curve of model 1 is stiffer than the experimental one. However, model 2 shows a fairly good prediction of the global behaviour due to the contact conditions, with friction allowing sliding at the dowel/hole interfaces, which corresponds to the progressive failure of the weld over a certain loading level. On the other hand, model 1, model 2, and experiment have same initial slopes. In fact, over the yield strength of the weld, the behaviour of the beam cannot be well predicted without dealing properly with the behaviour at the dowel/hole interfaces.

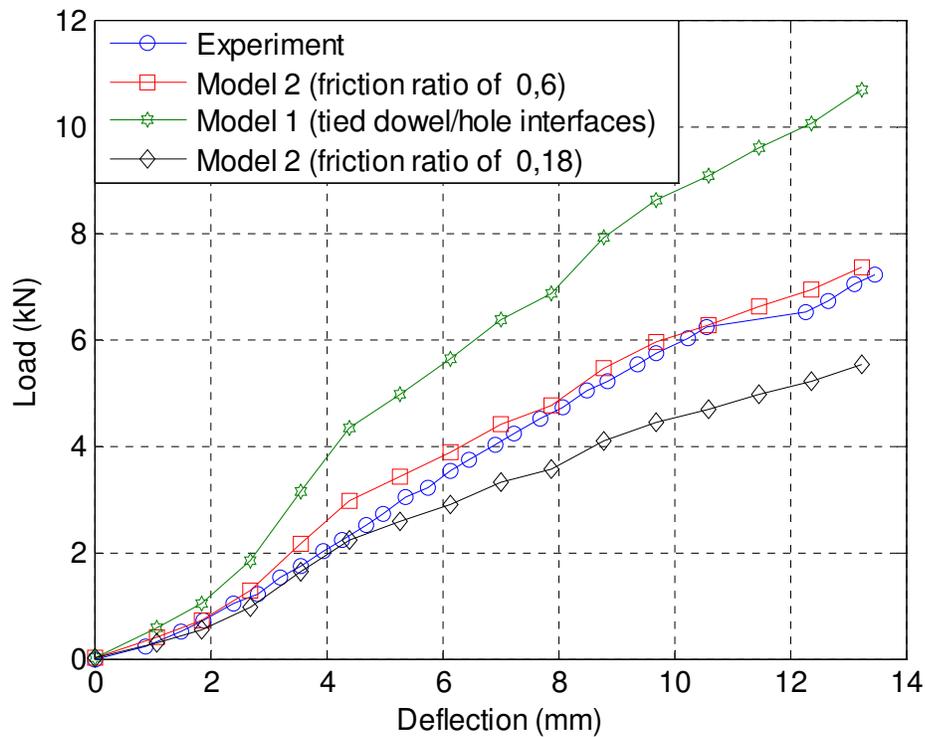


Fig. 6: Numerically predicted load–deflection curves: comparison with experiment

The numerically predicted distributions of the equivalent stresses in the layers and in the individual dowels are shown in Figs. 7 and 8, where it is clearly seen that the dowels get the largest equivalent stresses when compared to the layers.

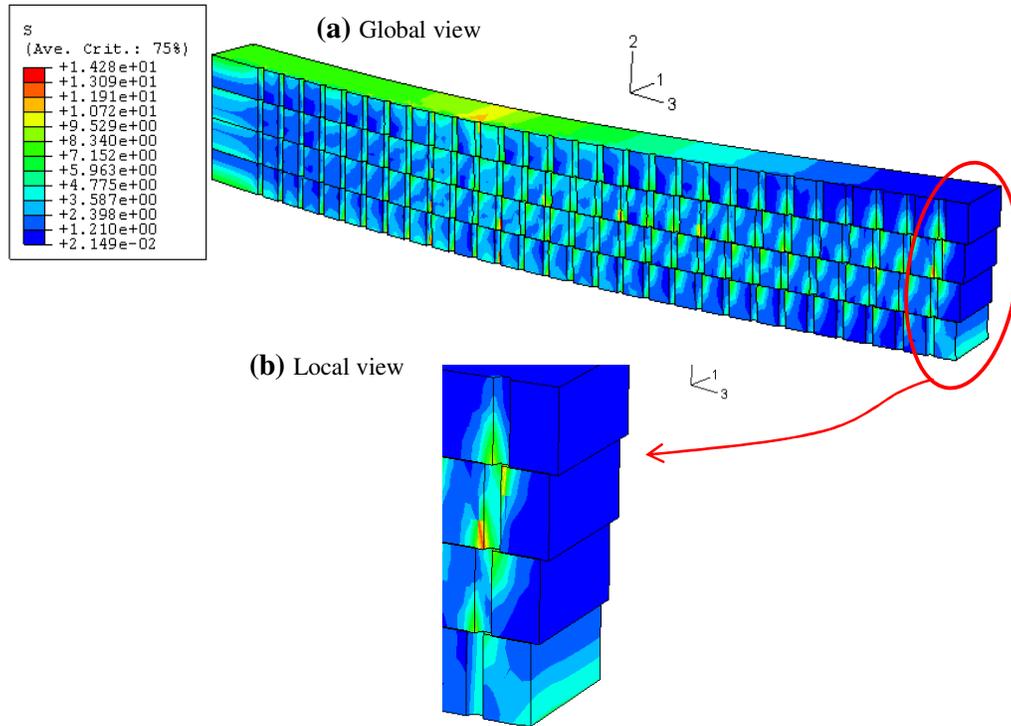


Fig. 7: Numerically predicted distribution of the equivalent stress in the layers

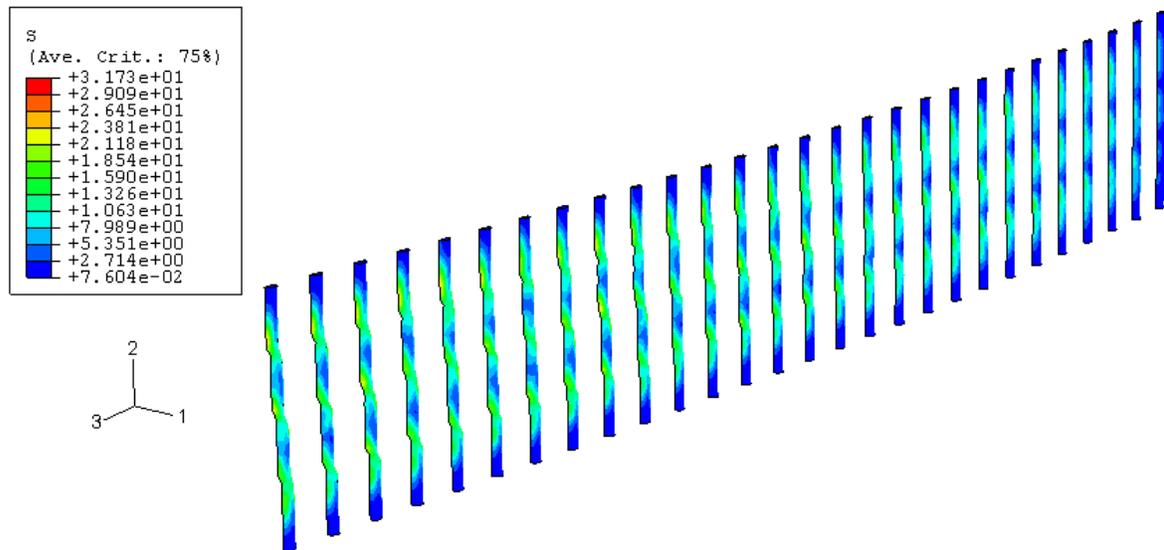


Fig. 8: Numerically predicted distribution of the equivalent stress in the dowels

The total contact forces, which combine both the normal and shear contact forces, on the individual dowels are shown for the groups 1 and 2 in Figs. 9 and 10, respectively. From these figures, one can observe the sequence order of the dowels getting contact forces.

It is interesting to see that the group 1, i.e. dowels 1 to 10, carries contact forces ranging from 0.3 to 1 kN, while the group 2 (dowels 11 to 28) bears contact forces ranging from 1 to 1.6 kN. Based on the curve slopes, it is also seen that the dowels of the group 2 pick up, first, contact loads in the beginning of the loading stage, then the dowels of group 1 start to contribute after the dowels of the group 2 get fully working. Thus it can be concluded that the initial stiffness of the layered beam is mainly due to the dowels near the support of the layered beam (group 1). Anyhow, contact forces on the dowels near the support of the beam remain highest.

This validated FE-model was, then, used to investigate the effect of some influential parameters on the bending strength of the wood-doweled layered beams.

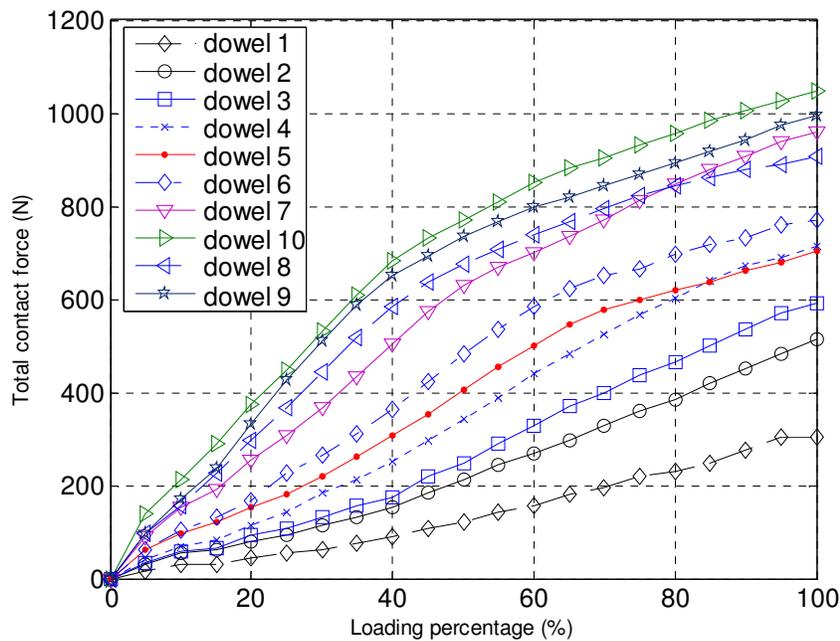


Fig. 9: Total contact forces versus the loading percentage for the group 1 of dowels

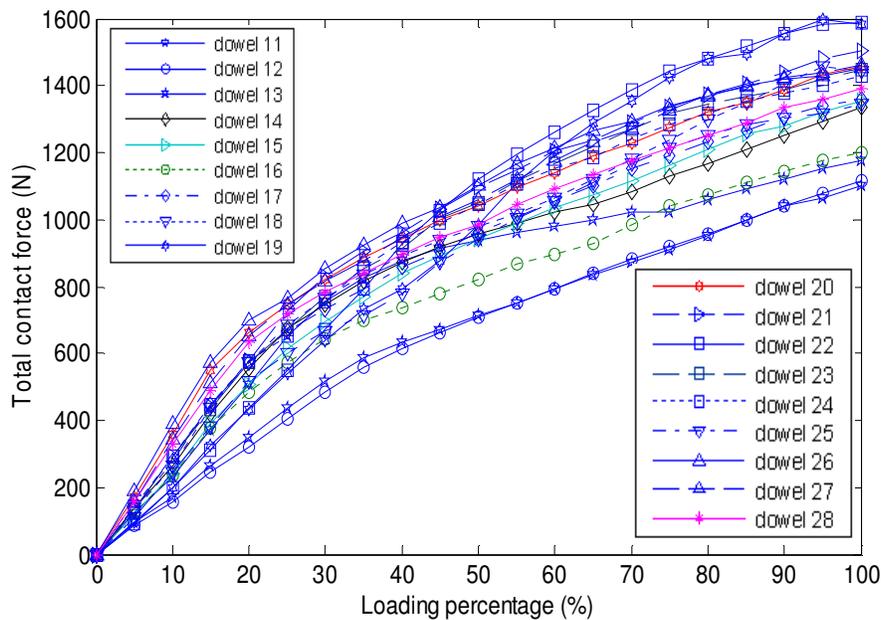


Fig. 10: Total contact forces versus the loading percentage for the group 2 of dowels.

4. Parametric study and discussions

To investigate the potential of multi-layered beams systems with welded wood dowels in terms of bending stiffness, a parametric study was undertaken assuming the four-layered beam, with one row of 56 dowels presented above (Section 2). In order to evaluate the change in bending behaviour of the layered beam brought about by changing some material and geometric parameters, a number of numerical simulations were run with the following configurations:

- the mechanical properties of the dowels;
- the thickness of the central layer (near the neutral plane);
- the mechanical properties of timber layers near the surface (top and bottom) ;
- the number of rows of dowels in the layered beam;

All load-deflection curves of the different studied configurations are plotted and compared against the initial configuration for control.

4.1. Influence of the mechanical properties of dowels

To understand the influence of the grade of wood dowels on the bending stiffness of the layered beams, the elastic properties of dowels are chosen as follows: $E_1 = 25500$ MPa, $E_2 = 2050$ MPa, $E_3 = 1170$ MPa [6]. The load-deflection curve obtained is displayed in Fig. 11 and compared to that obtained with the initial configuration. It can be seen that the influence of the dowel properties on the bending stiffness is significant. For a final displacement, the load was increased from 7.22 kN to 10 kN.

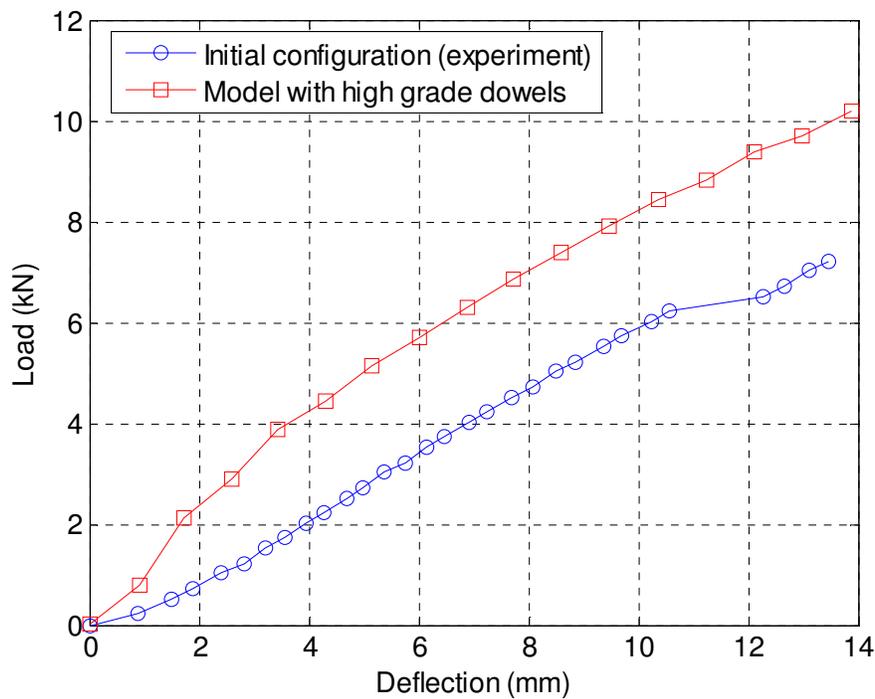


Fig. 11: Influence of material properties of dowels on the load–deflection curve.

4.2. Influence of the thickness of layers

In order to evaluate the difference between specimens with unequal layer thickness and those with equal layer thickness, it was decided to increase thickness of the layer near the

neutral plane, of greatest shear stresses, from 38 mm to 76 mm. This allows to absorb the maximum shear stress by solid wood layer that otherwise will be transferred through the individual wood dowels. From Fig. 12, one can observe that the effect of layer thickness is more prominent as compared to the specimens made with high grade wood dowels. This increase the load from 7.22 kN to 12 kN. Thus, it can be concluded that placing thicker layer near the neutral plane, bending stiffness of the layered beam can be significantly improved.

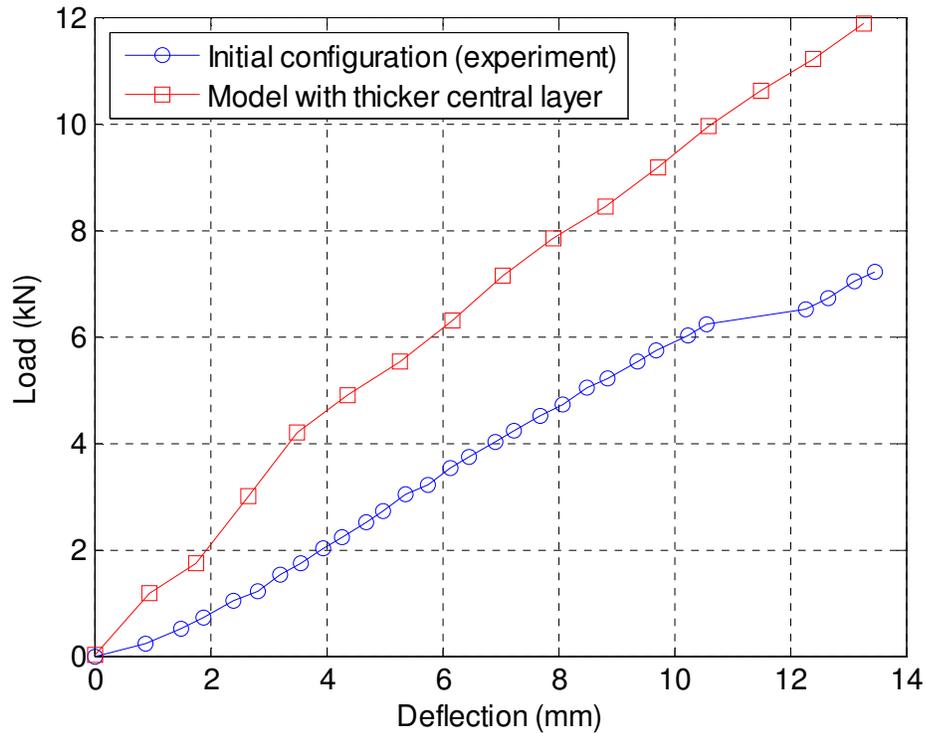


Fig. 12: Influence of layer thickness on the load–deflection curve.

4.3. Influence of the mechanical properties of layers near the beam surface

Glulam is generally manufactured by placing high grade layers on the extreme tension and compression faces, particularly in the case of a flexural member [2], to pickup greatest flexural stresses. In the same way, one wishes to evaluate the influence of material properties of layers near the beam surface on the bending stiffness. The elastic properties of both the extreme tension and compression layers are chosen as follows: $E_1 = 17500$ MPa, $E_2 = E_3 =$

700 MPa. The numerically computed load-deflection curve is displayed in Fig. 13 and compared to that obtained with the initial configuration, where one can observe a significant effect of the extreme layer properties on the bending stiffness, which is similar to the influence of dowel properties.

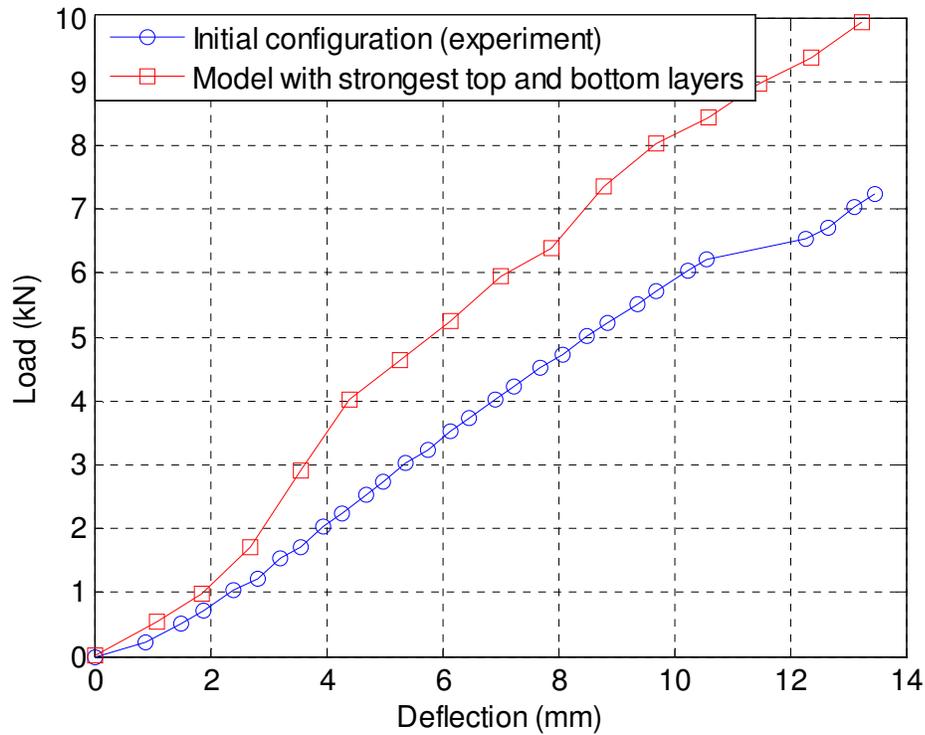


Fig. 13: Influence of mechanical properties of extreme tension and compression layers on the load–deflection curve.

4.4. Influence of the number of rows of dowels

Fig. 14 displays the load-deflection curve from the beam with two rows of dowels. For this beam configuration, the changes are relatively small compared to those obtained with the other studied configurations. The increase of load was only around 1 kN.

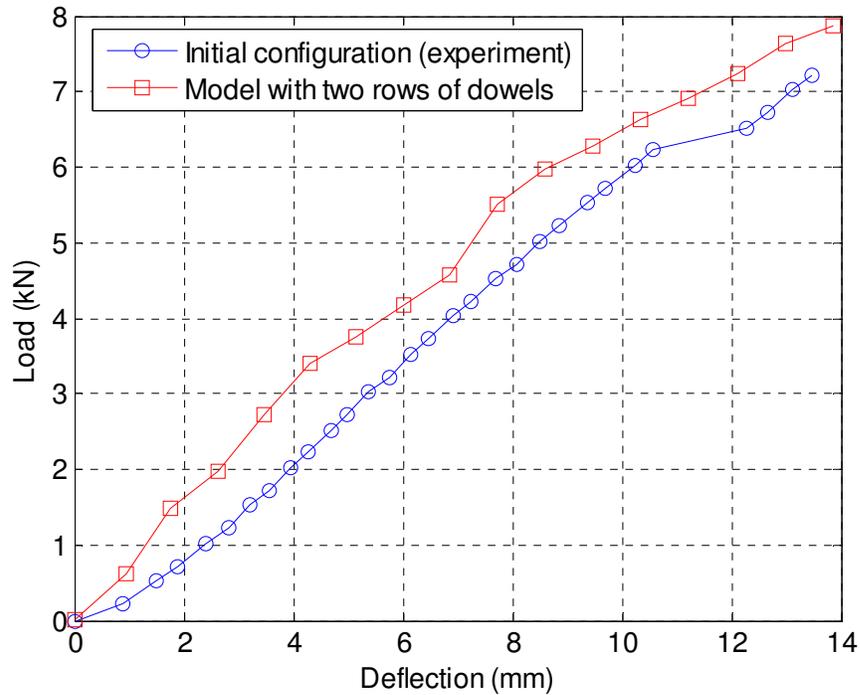


Fig. 14: Influence of number of rows of dowels on the load–deflection curve.

5. Conclusion

This paper have shown the feasibility of multi-layered wooden beams with welded wood dowels as an interesting alternative in place of traditional poly(vinyl acetate) (PVAc)-glued dowels and nailing. The use of wooden dowels in timber structural components is particularly promising and will be attractive, since it has a positive environmental impact.

To investigate the full potential of such beam systems, experimental tests need to cover as many scenarios as possible, such as material and geometric parameters, which is likely to be very expensive and time consuming. Thus, in order to understand thoroughly the behaviour of multi-layered beams with a very limited number of experimental studies, a 3D FE model was presented, validated against experimental results and then used to investigate some influential parameters.

The numerical modelling appears to be a fast and efficient numerical tool to thoroughly study such beam systems, since it is relatively inexpensive and allows to obtain information inaccessible by experiments, such as the contact forces acting in the dowels.

Numerical results have shown that a reasonable bending stiffness of multi-layered beams is achievable with a good combination of material and geometric parameters. Results have indicated that the material properties of dowels, the material properties of layers near the beam surface and the thickness of the layer near the neutral plane are the more influential parameters on the bending stiffness: the stronger properties of dowels and the extreme layers, the thicker the layer near the neutral plane, the higher the beam stiffness. The beams with equal layer thickness resulted in significantly lower bending stiffness than those with thicker central layer. The effect of the number of rows of dowels is not negligible but still lower than the other studied parameters. The developed FE model may be used in the future for further understanding of multi-layered welded dowel beam issues, optimisation, modulus of rupture, ductility and creep/relaxation behaviour, due to the moisture dependent, of beam systems are all fundamental engineering issues that should be addressed in a future research work.

References

- [1] B. Anshari, Z. Guan, K. Komatsu, A. Kitamori and K. Jung, Explore novel ways to strengthen glulam beams by using compressed Japanese cedar. Proceedings of the World conference on Timber Engineering (WCTE), 20-24 June 2010, Riva del Garda, Trentino (Italy), 8 pages.
- [2] Camille A. Issa and Z. Kmeid, Advanced wood engineering: glulam beams. Construction and Building Materials, Vol. 19 (2005), pp. 99 –106.
- [3] Guan Z.W., Rodd P.D., and Pope D.J., Study of glulam beams pre-stressed with pultruded GRP. Computers and Structures, Vol. 83 (2005), pp. 2476 – 2487.
- [4] B. Anshari, Z. Guan, K. Komatsu, Finite element modelling of the pre-camber of glulam beams reinforced by compressed wood. Proceedings of the World conference on Timber Engineering (WCTE), 20-24 June 2010, Riva del Garda, Trentino (Italy), 6 pages.

- [5] T. Dilik and S. Hiziroglu, Effect of density and some of the production parameters on bending strength of laminated window profiles. *Building and Environment*, Vol. 39 (2004), pp. 1199 – 1205.
- [6] Guan Z.W., Komatsu K., Jung K., and Kitamori A., Structural characteristics of beam-column connections using compressed wood dowels and plates. *Proceedings of the World conference on Timber Engineering (WCTE)*, 20-24 June 2010, Riva del Garda, Trentino (Italy), 6 pages.
- [7] Pizzi, A., Leban, J.M., Kanazawa, F., Properzi, M., Pichelin, F. (2004) ‘Wood dowel bonding by high-speed rotation welding’, *Journal of Adhesion Science and Technology*, Vol. 18, No 11 : p.1263-1278.
- [8] Vaziri, M., Lindgren, O., Pizzi, A. & Mansouri, H., Moisture sensitivity of Scots pine joints produced by linear frictional welding 2010 In : *Journal of Adhesion Science and Technology*. 24, 8, p. 1515-1527. 13 p.
- [9] Kanazawa, F., Pizzi, A., Properzi, M., Delmotte, L., Pichelin, F. (2005) ‘Parameters influencing wood-dowel welding by high-speed rotation’, *Journal of Adhesion Science and Technology*, Vol. 19, No 12 : p.1025-1038.
- [10] K. Jung, A. Kitamori and K. Komatsu, Evaluation on Structural Performance of Compressed Wood as Shear Dowel. *J. of Wood Science*, Vol. 62 (2008), pp. 461-467.
- [11] I. Hassel, P. Berard and K. Komatsu, Development of Wooden Shear Wall-Improvement of Stiffness by utilizing elements of densified wood, *Holzforchung*, Vol. 62 (2008), pp. 584-590.
- [12] Bocquet, J.F., Pizzi, A., Despres, A., Mansouri, H.R., Resch, L., Michel, D., Letort, F. (2007) ‘Wood joints and laminated wood beams assembled by mechanically-welded wood dowels’, *Journal of Adhesion Science and Technology*, Vol. 21, No 3-4 : p.301-317.
- [13] Oudjene M., and Khelifa M.: Finite element modelling of wooden structures at large deformations and brittle failure prediction. *Materials & Design* 30 (10): 4081-4087, 2009.
- [14] Oudjene M., and Khelifa M.: Elasto-plastic constitutive law for wood behaviour under compressive loadings. *Construction & Building Materials* 23 (11): 3359-3366, 2009.
- [15] Oudjene M., Khelifa M., Segovia C., and Pizzi A.: Application of Numerical Modelling to Dowel-Welded Wood Joints. *Journal of Adhesion Science and Technology* (24): 359-370, 2010.
- [16] Oudjene M. and Khelifa M., Experimental and numerical analysis of single double shear dowel-type timber joints. *Proceedings of the World conference on Timber Engineering (WCTE)*, 20-24 June 2010, Riva del Garda, Trentino (Italy), 6 pages.
- [17] M. Oudjene, J.-L. Batoz, L. Penazzi and F.Mercier, A methodology for the 3D stress analysis and the design of layered sheet metal forming tools joined by screws. *J. Mater. Proc. Technol.* 189, 334–343 (2007).

[18] M. Oudjene, L. Penazzi and J.-L. Batoz, Towards the three-dimensional FE analysis of rapid prototyping tools for sheet metal stamping process. *Finite Elements in Analysis and Design* 43, 611–619 (2007).