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Modified foundation modelling of dowel embedment in glulam connections

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HIGHLIGHTS

- The embedment behaviour of single-dowel connections in Scandinavian Spruce Glulam is examined.
- The evolution of local strain concentrations is reported in detail by means of non-contact field strain measurements.
- A modified foundation model is proposed and detailed Finite Element simulations are carried out.
- Relationships for the estimation of material characteristics as a function of the crushing volume are suggested.

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ABSTRACT

This paper examines the embedment behaviour of single-dowel connections in Scandinavian Spruce Glulam by means of experimental and numerical investigations. First, the experimental results of a series of single-dowel tests on samples of different geometry and grain directions are presented. The evolution of local strain concentrations around the fastener at increasing levels of bearing deformation, is reported in detail by means of non-contact field strain measurements and its implications are discussed. Detailed Finite Element simulations are also carried out and subsequently employed to highlight the main features of the response of doweled connections in glulam. A foundation model, initially developed for Douglas-fir (*Pseudotsuga menziesii*) timber, is upgraded and adapted for Scandinavian Spruce Glulam (*Picea abies*) elements subjected to loads acting perpendicular and parallel to the grain direction. The proposed model is based on the definition of equivalent material parameters for the crushing region around the dowel hole. To this end, relationships for the estimation of material characteristics as a function of the crushing volume are suggested. The validity and accuracy of the proposed modified foundation models are examined against the experimental results. It is shown the improved foundation model is able to simulate the embedment stiffness, capacity and inelastic behaviour of single-dowel connections on glulam with reasonable accuracy for strains of up to 8%, and can therefore be used for design and assessment purposes.

1. Introduction

Timber is an organic material made of cellulose fibres that exhibit complex mechanical behaviour. The difficulties associated with modelling the response of structural wood are accentuated when dealing with the behaviour of timber joints due to the intricate and highly non-linear interactions between the different connection components. Nevertheless, knowledge of the behaviour of timber joints is of paramount importance since they can govern the overall structural response and design. In this context, single-dowel connections constitute a common and basic component of timber joints. Therefore, to successfully design and assess timber joint details, accurate and reliable mechanical or Finite Element (FE) numerical models of single-dowel connections are required. In this context, orthotropic material theory has been successfully incorporated into FE simulations within the linear-elastic range. Nevertheless, more advanced methods are required to deal with the localised nonlinear behaviour of timber such as that arising from embedment effects.

Patton-Mallory et al. [1,2], implemented an orthotropic constitutive law for timber (Douglas-fir) in the commercial software ABAQUS [3] incorporating a tri-linear stress–strain compression response parallel to grain. The proposed model was able to simulate the experimental results but with a marked tendency towards a numerically stiffer response. Importantly, only compression parallel-to-grain was considered. Moses and Prion [4], studied the three-dimensional non-linear behaviour of a single-dowel

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timber connection test by means of a material model based on orthotropic elasticity and anisotropic plasticity together with the Weibull Weakest Link Theory to account for brittle failure. A good level of agreement between the numerically predicted force–displacement relationships and their corresponding experimental results was achieved. However, the estimation of ultimate loads was found to be over-conservative. Kharouf et al. [5] modelled bolted timber joints by assuming an elastic–plastic orthotropic Hill criterion for wood in compression and a linear-elastic orthotropic criterion for wood in tension. The model was able to reproduce the experimentally observed failure modes and global deformation patterns in one-bolt joints but with a numerical stiffness significantly larger than the experimental values.

In general, the computational implementation of advanced failure criteria, such as those reported in the above-cited studies, is highly complex and requires knowledge of advanced programming. Moreover, the difficulties associated with the definition of interactive failure modes and localised non-linear deformations further complicate their adoption. To this end, Foschi [6] proposed an approximate numerical two-dimensional model that takes into account the crunching behaviour of wood around the dowel by incorporating an equivalent circular area centred around the dowel with weakened material properties known as the 'foundation model'. More recently, Hong [7] extended the 'foundation' approach to three-dimensional continuum FE models representing bolted connections in Douglas-fir wood. Nevertheless, the dependence of the equivalent material properties on the volume assumed for the foundation zone was not investigated.

This paper revisits the foundation model for the simulation of the embedment behaviour in Scandinavian Spruce (*Picea abies*) with dowels. First, the results of an experimental campaign including compression, shear and embedment tests in the two main orientations with respect to the grain direction (perpendicular and parallel) are presented. The use of non-contact strain field measurements (DIC – Digital Image Correlation) to investigate the deformations around the embedding dowel is summarised. Particular attention is paid to the difference in the evolution of stress localisation brought about by the different orientations of grain. Finally, a modified foundation model is proposed for which relationships between equivalent material characteristics such as strength and stiffness as a function of the crushing volume are developed. In general, the improved foundation model proposed is able to simulate the embedment stiffness, capacity and inelastic behaviour of single-dowel connections on glulam with reasonable accuracy when compared with the experimental results.

2. Material characterisation

This section presents the results of a detailed material characterisation programme involving twenty-five (25) Scandinavian Spruce Glulam specimens subjected to shear loads and compression (parallel and perpendicular to grain). The tests were performed in accordance with European standard EN 408 [8]. Mean values of compressive strength in each of the principal directions as well as their corresponding shear resistance and Young's moduli were obtained and are summarised below. The species of the wood used was Scandinavian spruce (*P. abies*), with a mean density $\rho = 430\ \text{kg/m}^3$ and a moisture content of approximately 10%. All the specimens were stored in a dry environment with a mean temperature of 20 °C and a relative humidity of 60%.

2.1. Compressive resistance

A total of eight wood cubes of 45 mm × 45 mm × 45 mm were tested under compression parallel to the grain direction. A monotonically increasing load was applied to the specimen at a rate of 1 mm/min as depicted in Fig. 1. The applied load was measured with an accuracy of ±0.1 kN by means of the load cell incorporated within the testing apparatus. Table 1 summarises the dimensions and mean response parameters obtained from the compression tests parallel to the grain together with their related coefficients of variation (COV), whereas Fig. 2 presents the corresponding stress–strain relationships.

The mean compressive strength parallel to the grain, $\sigma_{c,0,Ti}$ reported in Table 1 was obtained by averaging the maximum strength values of each individual response. Similarly, the elastic modulus, $E_{c,0,Ti,i}$, of specimen i was estimated as:

$$E_{c,0,Ti,i} = \frac{(0.4F_{c,0,Ti,max,i} - 0.1F_{c,0,Ti,max,i})h_i}{(u_{0.4,i} - u_{0.1,i})A_i} \tag{1}$$

where, $F_{c,0,Ti,max,i}$ is the maximum compressive load reached by the timber specimen parallel to the grain, A_i is the area under stress, h_i is the specimen height (see Fig. 1), and $u_{0.1,i}$ and $u_{0.4,i}$ are deformation increments corresponding to 10% and 40% of $F_{c,0,Ti,max,i}$, respectively.

In addition to the material characterisation tests in the direction parallel to grain described above, nine tests on wood specimens subjected to compression perpendicular to the grain were also carried out. The perpendicular-to-grain specimens had dimension of 45 mm × 70 mm × 90 mm as illustrated in Fig. 3. This figure also presents the final test set-up employed. As before, the axial load was incrementally increased at a rate of 1 mm/min and measured with an accuracy of ±0.1 kN. Fig. 4 shows the results obtained from all compression tests perpendicular to the grain direction while Table 2 summarises the corresponding dimensions and response parameters as well as their coefficient of variation (COV). It can be appreciated from Fig. 4 that plastic deformations start to accumulate at low deformation levels (approximately 0.02 strain or 2 mm of vertical deformation) after which noticeable hardening occurs. Importantly, all specimens experienced a significant densification of the material for strains of approximately 0.2 (18 mm) during testing.

The elastic modulus in compression perpendicular to the grain for specimen i, $E_{c,90,Ti,i}$, was calculated as:

$$E_{c,90,Ti,i} = \frac{(0.4F_{c,90,Ti,max,i} - 0.1F_{c,90,Ti,max,i})h_i}{(u_{0.4,i} - u_{0.1,i})A_i} \tag{2}$$

where, $F_{c,90,Ti,max,i}$ is the maximum compressive load reached by the timber sample, A_i is the area under stress, h_i is the specimen height (see Fig. 3), and $u_{0.1,i}$ and $u_{0.4,i}$ are deformation increments corresponding to 10% and 40% $F_{c,90,Ti,max,i}$, respectively.

2.2. Shear resistance

Characterisation of the shear strength of the wood employed in this study followed the European Standard EN408 [8]. To this end, eight specimens of 55 mm × 32 mm × 300 mm were manufactured and subjected to shear forces as showed in Fig. 5. Two 10 mm thick steel plates were glued to each side of the specimen by means of a high strength high peel epoxy adhesive. The specimen was supported at an angle of 14° with respect to the vertical axis of the actuator with the help of full-contact metallic stands. A monotonically increasing vertical load, F, was applied at a constant rate of 0.4 mm/min.

Table 3 reports the obtained mean values and COV while Fig. 6 presents the results in terms of shear force versus engineering shear strain curves. The shear strength of each specimen was calculated as:

$$\sigma_{v,0,Ti,i} = \frac{F_{v,0,Ti,max,i}(\cos 14^\circ)}{A_i} \tag{3}$$