Modified foundation modelling of dowel embedment in glulam connections

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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.

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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 localized nonlinear behaviour of timber such as that arising from embedment effects.

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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 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 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 localized non-linear deformations further complicate their adoption. To this end, Fochi [6] proposed an approximate numerical two-dimensional model that takes into account the crushing 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 summarized. Particular attention is paid to the difference in the evolution of stress localization 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 characterization

This section presents the results of a detailed material characterization 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 summarized below. The species of the wood used was Scandinavian spruce (*Picea 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 mean temperature 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 Figure 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 summarizes the dimensions and mean response parameters obtained from the compression tests parallel to the grain together with their related coefficients of variation (COV), whereas Figure 2 presents the corresponding stress-strain relationships.

a) Specimen dimensions

b) Test set-up

Figure 1. Compression tests parallel to grain.

Figure 2. Compression stress-strain relationships for Scandinavian Spruce Glulam parallel to the grain direction

Specimen	A [mm ²]	h [mm]	Compressive strength $\sigma_{c,0,Ti}$ [MPa]	Young's Modulus $E_{c,0,Ti}$ [MPa]
Average	2023.2	45.2	39.6	2050.8
COV [%]	0.6	0.4	2.0	14.0

Table 1. Dimensions and characteristic parameters for Scandinavian Spruce glulam under compression parallel to grain.

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

$$5 \quad E_{c,0,Ti,i} = \frac{(0.4F_{c,0,Ti,max,i} - 0.1F_{c,0,Ti,max,i})h_i}{(u_{0.4,i} - u_{0.1,i})A_i} \quad (1)$$

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

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10 In addition to the material characterization tests in the direction parallel to grain described above,
 11 nine tests on wood specimens subjected to compression perpendicular to the grain were also carried
 12 out. The perpendicular-to-grain specimens had dimension of 45 mm $\times$ 70 mm $\times$ 90 mm as
 13 illustrated in Figure 3. This figure also presents the final test set-up employed. As before, the axial
 14 load was incrementally increased at a rate of 1 mm/min and measured with an accuracy of ± 0.05
 15 mm. Figure 4 shows the results obtained from all compression tests perpendicular to the grain
 16 direction while Table 2 summarizes the corresponding dimensions and response parameters as well
 17 as their coefficient of variation (COV). It can be appreciated from Figure 4 that plastic deformations
 18 start to accumulate at low deformation levels (approximately 0.02 strain or 2 mm of vertical
 19 deformation) after which noticeable hardening occurs. Importantly, all specimens experienced a
 20 significant densification of the material for strains of approximately 0.2 (18 mm) during testing

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22 The Elastic Modulus in compression perpendicular to the grain for specimen i , $E_{c,90,Ti,i}$, was
 23 calculated as:

$$24 \quad E_{c,90,Ti,i} = \frac{(0.4F_{c,90,Ti,max,i} - 0.1F_{c,90,Ti,max,i})h_i}{(u_{0.4,i} - u_{0.1,i})A_i} \quad (2)$$

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

Figure 3. Compression tests perpendicular to grain.

Figure 4. Compression stress-strain relationships for Scandinavian Spruce Glulam perpendicular to the direction of the grain

Specimen	A [mm ²]	h [mm]	Compressive strength $\sigma_{c,90,Ti}$ [MPa]	Young's Modulus $E_{c,90,Ti}$ [MPa]
Average	3082.1	89.9	2.5	172.1
COV [%]	0.2	0.2	8.5	9.5

Table 2. Dimensions and characteristic parameters for Scandinavian Spruce glulam under compression perpendicular to grain.

2.2 Shear resistance

Characterization 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 Figure 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 Figure 6 presents the results in terms of shear force versus engineering shear strain curves. The shear strength of each specimen was calculated as:

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

where, $F_{v,0,Ti,max,i}$ is the maximum compressive load reached and A_i is the area under stress ($h_i \cdot l_i$).

Figure 5. Shear test.

Figure 6. Shear force-displacement relationships for Scandinavian Spruce Glulam.

Specimen	A [mm ²]	b [mm]	Shear strength $\sigma_{v,0,Ti}$ [MPa]	Shear Modulus $G_{12,Ti}$ [MPa]
Average	9651.7	54.8	5.0	192.3
COV [%]	0.3	0.4	5.9	12.3

Table 3 – Summary of test results for glulam timber specimens under shear loads.

3. Embedment tests

A total of thirty-seven (37) embedment tests were conducted including load directions parallel and perpendicular to the grain. Two dowel diameters, $d = 12$ mm and $d = 16$ mm, were employed. The tests were carried out in accordance with the European EN 383 Specification [9]. Figure 7 shows a typical view of an embedment test with load acting parallel to the wood grain direction. Tests were conducted on twelve specimens with 12 mm steel dowels and eight specimens with a 16 mm dowels. All dowels were made of high strength steel of Grade 10.9. A constant rate of 1 mm/min was applied to the dowels by means of a purpose-built metallic assembly consisting of two steel side plates 100 mm wide and 20 mm thick welded and bolted together via a spacer steel block. The load and displacement at the centreline of the dowel were constantly recorded with accuracies of ± 0.1 kN and ± 0.05 mm, respectively.

Figure 7. Experimental set-up of one-dowel connection test parallel to grain (left) and perpendicular to grain (right) for 12 mm dowels.

3.1 Mean values of strength and stiffness

Tables 4 and 5 below, summarize the results of embedment tests performed in the parallel and perpendicular-to-grain directions, respectively. These tables include the number of specimens, specimen dimensions, mean embedment strength, mean embedment Elastic modulus and their corresponding coefficients of variation (COV). A bi-linear approximation was employed to calculate the values of strength and Elastic modulus reported in Tables 4 and 5. To this end, elastic-plastic relationships were obtained by employing two lines tangent to the elastic and post-elastic branches of the experimental force-displacement curves as depicted in Figure 8. Accordingly, the embedment stress $\sigma_{a,Emb}$ and Elastic modulus $E_{a,Emb}$ for each specimen can be determined as:

$$\sigma_{a,Emb} = \frac{F_{y,a,emb}}{d \times t} \quad (4)$$

$$E_{a,Emb} = \frac{k_{a,emb}}{t} \quad (5)$$

where $F_{y,a,emb}$ is the embedment force at the yield point, u_{emb} is the embedment in the timber in [mm], $k_{a,emb}$ is the slope of the force-embedment curve in the linear-elastic region in [kN/mm] and d and t are the dowel diameter and specimen width in [mm], respectively.

d [mm]	Number of specimens		Width [mm]	Height [mm]	Thick [mm]	Embedment strength $\sigma_{0,Emb}$ [MPa]	Embedment Elastic modulus $E_{0,Emb}$ [MPa]
12	12	Mean	120.0	168.0	40.0	29.4	376.0
		COV [%]	0.1	0.1	0.5	7.9	15.4
16	8	Mean	160.0	224.2	40.5	29.6	1033.9
		COV [%]	0.1	0.1	0.4	8.7	17.3

Table 4. Summary of embedment tests under loads parallel to the direction of the grain.

d [mm]	Number of specimens		Width [mm]	Height [mm]	Thickness [mm]	Embedment strength $\sigma_{90,Emb}$ [MPa]	Embedment Elastic modulus $E_{90,Emb}$ [MPa]
12	8	Mean	479.7	119.3	39.8	14.7	136.8
		COV [%]	0.1	0.3	0.9	11.9	30.7
16	9	Mean	640.3	159.4	40.3	14.6	240.8
		COV [%]	0.1	0.1	0.5	17.2	7.1

Table 5. Summary of embedment tests under loads perpendicular to the direction of the grain.

Figure 8. Typical experimental force-embedment curves and their corresponding bi-linear approximations (dowel diameter $d = 12$ mm)

3.2 Embedment response parallel to the grain direction

Figure 9 shows the results obtained from the embedment tests on glulam with 12 mm and 16 mm dowels. An initial relatively flexible stage is evident from this figure for loads lower than 2 kN. This behaviour is attributed to the non-uniform contact and initial clearance existing between the dowel and the timber material, which leads to the rapid accumulation of localized deformations. Once a uniform contact is attained along the full embedment width, a linear stage develops with forces increasing in direct proportion to the deformation until they reach the embedment strength of

the specimen, after which a third behavioural stage develops. This final response stage corresponds to deformations greater than 0.8 mm and 0.5 mm embedment for 12 and 16 mm dowels, respectively and is characterized by a largely plastic response as can be observed in Figure 9.

Mean embedment strength values of 29.4 MPa and 29.6 MPa are observed for the 12 and 16 mm doweled connections, respectively. These values can be compared to the embedment strengths assumed by Eurocode 5 [10] calculated as:

$$\sigma_{0,Emb,DX,k} = 0.082 \times (1 - 0.01d)\rho \quad (6)$$

where, $\sigma_{0,Emb,DX,k}$ is the characteristic embedment strength for X dowel diameter, d is the diameter of the dowel and ρ is the density of the timber specimen. By introducing the corresponding values into Equation 7, mean characteristic embedment strengths of 31.1 MPa and 30.2 MPa are obtained for 12 mm and 16 mm dowels, respectively. These values are in close agreement with the experimentally obtained mean embedment resistances. Similarly, mean Young's modulus values of 376.0 MPa and 1033.9 MPa were observed for the connections with 12 mm and 16 mm dowels, respectively. It is evident from the results reported in Figure 9 and Table 4 that the larger the dowel diameter the stiffer the response.

Figure 9. Force-embedment relationships in the direction parallel to grain.

3.3 Embedment response perpendicular to the grain direction

A total of eight tests were performed with a 12 mm diameter dowel pushed in the direction perpendicular to the wood grain, while nine specimens were tested with a 16 mm diameter dowel. The experimental procedure followed was identical to the one previously described for embedment tests parallel to the grain direction. Figure 10 summarizes the results in terms of force-embedment curves while Table 5 presents the mean values and COV for strength and Elastic modulus.

Figure 10. Force-embedment relationships in the direction perpendicular to grain.

The embedment behaviour in the direction perpendicular to the grain follows the general trends already identified before for parallel-to-grain specimens where three behavioural stages are evident from Figure 10. An initial stage where the contact area between dowel and timber increases progressively up to a displacement of 0.1 mm is followed by an elastic stage up until the embedment strength of wood is realised at around 7.3 kN for 12 mm dowels (1.8 mm of embedment) and 9.7 kN for 16 mm dowels (1.2 mm of embedment). On the other hand, a marked post-elastic hardening behaviour is observed for embedment in the direction perpendicular to grain (Figure 10), which is not evident when the load is applied in the parallel-to-grain direction (Figure 9). The crushing of the fibres underneath the dowel and the associated densification of wood in the contact area cause this hardening response. This can be further studied with reference to the DIC measurements presented in the following section.

3.4 Non-contact field strain measurements

To investigate the localisation of strains around the embedment area, a LaVision [11] Digital Image Correlation (DIC) system was employed. Two cameras were employed in order to reduce the potential in-plane two-dimensional measurement errors associated with small out-of-plane motion. A full description of the binocular stereovision principles on which the DIC technique is based is outside the scope of the present study and more detailed information can be found elsewhere [12]. Figure 11 presents a view of the experimental set-up together with the DIC instrumentation utilized. Two cameras spaced at 500 mm from each other were placed at a distance of 1200 mm from the specimen. The cameras were rotated 15° as presented in Figure 11. High quality images were captured during the testing of the specimen at a rate of 31 frames per minute. Calibration of the focus areas was conducted by means of a $200 \times 200 \text{ mm}^2$ calibration plate while the specimens were prepared by spraying a randomized pattern of dots into the face where strains were to be measured. The DIC algorithm [13] tracks the motion of surface patterns during the experiment and calculates the corresponding 2D strain fields in each picture.

Figure 11. Experimental set-up with the DIC system. Embedment tests on a 12 mm dowel specimen.

Figures 12 and 13 show typical relative deformation contours obtained by means of the DIC system previously described together with their corresponding force-embedment curves for parallel-to-grain and perpendicular-to-grain specimens, respectively. Only the contours corresponding to the left bottom quarter of the specimen, below the dowel hole, are presented due to symmetry. It is evident from Figure 12, which presents the results for loading parallel to the grain, that as the embedment progresses, the area with largest relative displacement (shown in purple) also increases. Also, beyond 1.5 mm of embedment deformation, noticeable accumulation of localized damage around the dowel was evident during the experiment.

Figure 12. Force-embedment curve from the embedment test perpendicular to the grain ($d = 12$ mm)

Similarly, Figure 13 shows the force-embedment curve together with the relative displacement contours at four key behavioural stages for a perpendicular-to-grain test that employs a 12 mm dowel. In this figure, the area of largest concentration of deformations (purple) decreases in size as the embedment increases while a more pronounced horizontal orientation of contours relative to Figure 12 is evident.

Figure 13. Force-embedment curve from the embedment test perpendicular to the grain ($d = 12$ mm)

These differences in the evolution of areas of high deformation between parallel-to-grain (Figure 12) and perpendicular-to-grain (Figure 13) specimens can be attributed to the different mechanisms of load resistance involved as schematically shown in Figure 14. In parallel-to-grain loading, local buckling of some of the vertical fibres in direct contact with the dowel occurs at large deformation levels. With increasing demands, the confining action of the surrounding vertical fibres will favour a further concentration of deformation in the already buckled fibres directly below the dowel hence engaging more material underneath the dowel in the same direction of loading. On the other hand, when the action is applied perpendicular to the direction of the grain, the displacement of wood material tends to localize on the upper fibres with the lower fibres acting as an elastic foundation. This behaviour will encourage the concentration of non-linear response on the upper fibres once they have yielded while spreading the deformation field horizontally as observed in Figure 13.

Figure 14. Interaction between the embedment force and the fibre orientation.

These differences in strain localization brought about by the changes in fibre orientation with respect to the direction of load application can be further studied with reference to Figures 15 and 16 which present the y-displacement contours at maximum embedment force for parallel-to-grain and perpendicular-to-grain specimens, respectively. It can be seen from these figures that the area under analysis is located 3 mm below the hole in the left-side of the YZ-symmetry plane. Similarly, it can be seen from the contour plots of Figures 15 and 16, that the vertical distance along which the greater concentration of displacements is located is approximately 20 mm when the maximum load is applied parallel to the grain direction (Figure 15) while it is half of this (10 mm) when the maximum load is applied perpendicular to the grain direction. The effects of grain orientation on the main directionality of the strain field are also evident from Figures 15 and 16 with the contours tending to follow the grain orientation over the whole strain field computed. Finally, it is worth noting that the maximum absolute values of y-displacement in Figures 15 and 16 are 0.15 and 0.18 mm, respectively. This indicates that more than 80 % of the total embedment displacement (~ 0.85 mm for Figure 15 and ~ 0.84 mm for Figure 16) is concentrated within the area in close proximity

1 to the hole (e.g. within 3 mm from the dowel surface in the case of parallel to grain loading as
 2 presented in Figure 15).

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6 Figure 15. Displacement contours of one-dowel connection test, parallel to grain with a 12 mm
 7 dowel at maximum embedment force (~1.0 mm of vertical displacement)

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11 Figure 16. Displacement contours of one-dowel connection test, perpendicular to grain with a 12
 12 mm dowel at the yield point (~1.02 mm of vertical displacement)

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1 **4 Modified foundation model**

2 From the previous discussion, it can be appreciated that the response of dowel type connections is a
3 complex multi-dimensional problem for which modelling is not feasible through conventional
4 Finite Element (FE) programs by assuming standard or test-based material properties. This is
5 because conventional continuum FE programs lack the ability to simulate the intricate bearing
6 phenomena of the wood matrix. Figure 17 presents a typical comparison between a force-
7 embedment deformation response obtained by means of a FE model and its corresponding
8 experimental results for a 12 mm diameter dowel. The FE simulation is based on a continuum FE
9 representation of wood by means of an anisotropic yield criterion applied homogeneously
10 throughout the specimen (i.e. no difference is made between the material characteristics of the main
11 timber body and the zone surrounding the dowel as will be done later when a foundation zone is
12 introduced). Besides, the experimental results are represented in Figure 17 by their corresponding
13 upper and lower bound curves (or envelope) that mark the limits of the experimentally observed
14 force-embedment responses. Significant differences between the predicted and observed response
15 are evident from Figure 17. These differences, which are more apparent in the post-elastic range
16 stem from the effects of the evolution of the area/volume of strain concentration around the hole
17 leading to a complex response as explained in the previous section. These intricacies in the
18 mechanical behaviour of wood can be approximated in the FE simulation by incorporating a region
19 around the hole with empirically calibrated material properties, which is referred herein as the
20 ‘foundation zone’ [6].

Figure 17. Comparison between experimental embedment force-displacement response and FE simulation for parallel to grain direction

In light of the above discussion, the *foundation zone* approach, initially proposed by Foschi [6] for Douglas-fir (*Pseudotsuga menziesii*) emerges as an alternative solution with the potential for incorporating the effects of localized wood crushing into a FE simulation in a simple yet effective way. Figure 18 depicts the FE implementation of the foundation model approach for the simulation of a single-dowel connection embedment response. The method hinges around the incorporation of a modified material model within a certain volume around the dowel hole. This volume is referred to as the foundation zone (presented in white in Figure 18) for which the properties are determined via calibration procedures. In its original form, the foundation model assumed a cylindrical volume with a constant radius of 2.8 times the dowel diameter. This value was selected on the basis of experimental constraints related to the maximum size of the specimen tested [6] and no rational justification was offered. Furthermore, no provision was made for the use of the method when alternative geometric constraints may govern the definition of the foundation zone dimensions. In this section, the foundation material model is modified and extended for the case of Scandinavian Spruce Glulam. Also, a non-arbitrary procedure for the definition of material parameters within the foundation zone as a function of its volume are discussed and implemented.

Figure 18. Implementation of a single-dowel foundation FE model

4.1 Numerical modelling

Detailed 3D models were constructed by means of the FE program ABAQUS V6.14 [15]. A typical model is illustrated in Figure 18. This model makes use of eight-node brick solid elements of Type C3D8. It can also be appreciated from Figure 18 that symmetry conditions were used in order to save computational resources. A tri-linear kinematic hardening representation with an elastic modulus of 210 GPa and a Poisson's ratio of 0.3 was employed for the steel dowels. This steel stress-strain relationship incorporates an elastic stage, a constant stress plateau up to a strain level of approximately 0.01, and a 1 % strain-hardening stiffness thereafter. Importantly, all steel dowels remained elastic during the experiments and this was also reflected in the numerical simulations. Similarly, the experimentally obtained mean material properties described above were adopted for the wood. Modified values of strength and stiffness were employed for the wood within the foundation zone as described in the next section.

Contact phenomena between steel and wood were modelled by defining pairs of “master” and “slave” contact surfaces in ABAQUS. To this end, the relatively more flexible wood surface was defines as “slave” whereas the stiffer steel dowel surface was chosen as “master”. The hard contact over-closure pressure relationship of ABAQUS was modified by adopting a linear relationship with significantly stiff response to minimise non-convergence. A friction coefficient of $\mu=0.7$ was adopted as proposed by Smith [14]. The nodes at the two opposite ends of the dowel were progressively moved downwards along the y-axis and the corresponding vertical reaction forces at the base nodes were recorded.

A number of mesh size sensitivity studies were carried out in order to arrive at an optimum element size distribution. The adopted mesh arrangement involved a coarser mesh within the main body of the wood sample, whereas a finer mesh was employed for the foundation zone around the dowel hole. The dimensions of the finally adopted mesh ranged between 1 mm and 5 mm

4.2 Foundation zone material properties

Mean material properties from the previously described testing campaign were adopted for the main wood volume (outside the foundation zone). On the other hand, relatively softer and weaker material parameters were adopted for the foundation zone. Table 6 presents the ratios between the material parameters as obtained from embedment tests (identified by the subscript *Emb*) and those measured from direct compression tests (identified by the subscript *m*) the indices 1 to 3 refer to the three principal stress directions. These ratios were employed to define a basic set of material parameters for the foundation region. In the case of Poisson ratios and shear strengths, nominal values were assumed regardless of the foundation zone distinction. Similarly, the values for the shear modulus *G* introduced into the foundation zone were estimated from the empirical formula given in the annex of EN 338:2009 [16] as:

$$G_{12} = \frac{E_{11}}{16} \quad (7)$$

	d = 12mm	d = 16 mm
$E_{1,Emb}/E_{1,m}$	0.183	0.504
$E_{2,Emb}/E_{2,m} = E_{3,Emb}/E_{3,m}$	0.795	1.398
$G_{12,Emb}/G_{12,m} = G_{13,Emb}/G_{13,m}$	0.122	0.122
$G_{23,Emb}/G_{23,m}$	0.0122	0.0122
$\sigma_{11,Emb}/\sigma_{11,m}$	0.743	0.746
$\sigma_{22,Emb}/\sigma_{22,m} = \sigma_{33,Emb}/\sigma_{33,m}$	5.795	5.748

Table 6 – Material properties for the foundation modelling approach.

The original foundation zone approach for 3D models as proposed by Hong [7] assumes a constant radius $R_{FZ} = 1.4d$ for the foundation zone thus disregarding any variation in the definition of a weakened volume and its effects on the corresponding weakened material characteristics. This can limit the applicability of the method when the connection to be modelled is part of a different geometrical arrangement. In order to overcome those limitations, the radius of the foundation zone (R_{FZ}) is expressed herein in terms of the dowel diameter (d) by means of a ratio P such that:

$$R_{FZ} = P \cdot d \quad (8)$$

Furthermore, on the basis of extensive parametric analyses, the following expressions are proposed herein for the determination of effective Elastic Modulus within the foundation zone in the directions parallel ($E_{1,FZ}$) and perpendicular ($E_{2,FZ}$) to the grain direction:

$$E_{1,FZ} = \left(1 + \beta_1 \frac{P}{t}\right) E_{1,Emb} \quad (9)$$

$$E_{2,FZ} = \left(1 + \beta_2 \frac{P}{t}\right) E_{2,Emb} \quad (10)$$

where, t is the thickness of the specimen in [mm], E_{Emb} is the Young's modulus determined from the embedment tests in [MPa], E_{FZ} is Young's modulus of the foundation zone in [MPa] and β_1 and β_2 are empirical parameters for which optimal values are reported in Table 7 below

Parameter	d = 12 mm	d = 16 mm
β_1	6.27	2.28
β_2	5.51	3.13

Table 7 – Values for parameters β_1 and β_2 as a function of the dowel diameter.

Similarly, the following expressions are proposed for the estimation of yield stresses in the directions parallel ($E_{1,FZ}$) and perpendicular ($E_{2,FZ}$) to the grain direction:

$$\sigma_{11,FZ} = \left(1 - \gamma_1 \frac{P}{d \cdot t}\right) \sigma_{11,Emb} \quad (11)$$

$$\sigma_{22,FZ} = \left(1 - \gamma_2 \frac{P}{d \cdot t}\right) \sigma_{22,Emb} \quad (12)$$

where, t is the thickness of the specimen in [mm], d is the diameter of the dowel in [mm], σ_{Emb} is the stress determined from the embedment tests in [MPa], σ_{FZ} is the stress of the foundation zone in [MPa] and γ_1 and γ_2 are parameters for which values can be found in Table 8 for 12 mm and 16 mm dowels.

Parameter	d = 12 mm	d = 16 mm
γ_1	14.67	14.60
γ_2	21.57	21.74

Table 8 – Values for parameters γ_1 and γ_2

4.3. Comparison with test results

The modified foundation model proposed in the previous section was validated against the results of the laboratory tests described in Section 2. Figure 19 presents the comparisons between the force-displacement envelopes predicted by the modified foundation model and the experimental results when a 12 mm dowel is employed, while Figure 20 depicts the same comparisons for the case of 16 mm dowels. The experimental envelope was obtained by plotting the observed maximum and minimum forces along the full embedment range while the numerical results were obtained from the modified foundation model described above assuming P ratios in the range of 1.5 to 3. Figures 19 and 20 demonstrate that the estimations of the modified foundation model are in close agreement with the experimental results. The model is able to reproduce key response parameters such as stiffness and embedment strength well within the bounds of the experimentally observed values in all cases. In particular, the experimental force-displacement relationships of parallel to grain specimens (Figures 19a and 20a) is well simulated up to displacements of 4 mm (i.e. strain levels of around 8 %). However, in the case of perpendicular to grain response, the foundation model produces noticeable differences in the post-elastic range with appreciable strain hardening in the numerical estimations in lieu of the almost perfectly-plastic response observed in the experiments. This is attributed to the inability of the continuum FE model to reproduce localized splitting between fibres at large deformations and the associated softening effects. Nevertheless, the foundation model provides estimates within the experimentally observed bounds for embedment displacements of up to 2.5 mm in both cases (Figures 19b and 20b). An important feature of the

numerical responses presented in Figure 19 and 20 is their relatively low dependence on the radius of the foundation volume adopted (characterized here by the parameter P as introduced in Equation 8). This provides confidence in the effectiveness of Equations 9 to 12 in liberating the numerical response from a unique value of the foundation zone radius making the model consistently applicable to a wider range of varying geometrical configurations.

Figure 19. Comparison of experimental and numerical force-embedment envelope relationships ($d = 12$ mm).

Figure 20. Comparison of experimental and numerical force-embedment envelope relationships ($d = 16$ mm).

Finally, Figures 21 and 22 compare the experimentally observed displacement contours obtained by means of the DIC against the numerical predictions of the modified foundation model at yield for two representative parallel-to-grain and perpendicular-to-grain specimens, respectively. It is evident from these figures that the proposed foundation model is able to replicate the general tendencies in magnitude and distribution of the deformations within the specimens. A concentration of relatively higher localized strains immediately below the dowel are predicted by the FE model which can be attributed to the numerical definition of hard contact between timber and steel and the averaged nature of the material properties employed for the foundation model. Nevertheless, a good correlation of mean displacement orientations is apparent from Figures 21 and 22 including the effects of grain direction on the predominant contour alignment as discussed above.

Figure 21. Comparison of experimental and numerical displacement contours at yield. Embedment parallel to grain ($d = 12$ mm)

Figure 22. Comparison of experimental and numerical displacement contours at yield. Embedment perpendicular to grain ($d = 12$ mm)

5. Conclusions

This paper has studied the embedment behaviour of single-dowel connections in Scandinavian Spruce with loads acting parallel and perpendicular to the grain direction. An experimental programme comprising 39 connection details with 12 mm and 16 mm dowels was described. The tests enabled detailed monitoring of the evolution of local strain concentrations around the fastener at increasing levels of bearing deformation by means of Digital Image Correlation (DIC) techniques. This served to examine the tendency of the strain contours to align with the direction of the grain. Also, the differences in load bearing mechanisms brought about by the different grain orientations were found to influence the degree to which strain concentrations are able to penetrate in the wood material beneath the dowel area. To this end, significant increments in the highly strained area for parallel-to-grain specimens were observed in comparison with perpendicular-to-grain joints where a tendency towards an increasingly more localized concentration of the area of highest strains was documented.

1 A foundation model initially developed for Douglas-fir (*Pseudotsuga menziesii*) timber was
2 improved and adopted in this study to model the embedment response of Scandinavian Spruce
3 Glulam (*Picea abies*). The proposed model is based on the definition of equivalent material
4 parameters for the crushing region around the dowel hole. In order to improve the versatility of the
5 FE simulations, new relationships for the estimation of material characteristics as a function of the
6 crushing volume were suggested. The validity and accuracy of the proposed modified foundation
7 models were examined against the experimental results, and good agreement was found between the
8 experimental response and the numerical simulations, although this needs to be examined further in
9 future studies covering alternative joint configurations and loading conditions (such as the influence
10 of group effects and other edge conditions). Overall, the results presented in this paper suggest that
11 the proposed modelling procedures can be employed in the assessment and design of single-dowel
12 joints or as the basis for the formulation of alternative simplified approaches.

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