

# Numerical simulation of embedding strength of glued laminated timber for dowel-type fasteners

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**Abstract** A non-linear material model is proposed to describe the timber behavior. Anisotropic elasto-plastic constitutive law with hardening according to Hill yield criterion was used for the compressive behavior. Brittle behavior in tension and shear was modeled using the modified Hill failure criterion. The material model was implemented in a finite element code to simulate embedding strength of glued laminated timber for dowel-type fasteners. Reasonable agreement is found between numerical simulations and experimental measurements.

**Keywords** Dowel-type fasteners · Embedding strength · Finite element · Non-linearity

## Introduction

Glued laminated timber, also called Glulam, is the most popular structural timber product in heavy wood constructions. In fact, glulam is the only engineered wood product that can be produced in curved shapes, offering unlimited design flexibility. It is available in a range of appearance characteristics to meet end-use requirements.

In the timber structures, the connections are usually made with dowel-type fasteners and steel plates.

According to the current European code for timber structures [1], the design of dowel-type timber connections is based on the European Yield Model proposed by Johansen [2]. Embedding strength (or dowel-bearing strength) is one of the key material property parameters for timber joint design based on this theory. Two embedding test methods are standardized such as in the EN383 standard [3] and ASTM D 5764-97a [4]. Figure 1 shows the embedding test arrangements applied in the European and American methods. The European test method is based on the principle of reproducing the behavior of doweled connection but with short fastener to limit its bending deformations. Both tensile and compressive embedment testing modes are considered to take account of different stress distributions that prevail in real joints under lateral load. The clearance left between the fastener and the side-plates of the apparatuses minimizes the friction with crushed wood, but at the same time introduces the risks of increasing fastener deformations in bending during testing [5]. The American test method applies uniform contact along the fastener length during loading.

In addition to the test method, the definition of embedding strength is different in European and American standard. The embedding strength in the European method is calculated from the maximum load attained or the load corresponding to 5 mm of embedding displacement when the maximum load is not attained. The American method uses a 5 % diameter offset load to calculate the embedding strength. A comparison of the European and American procedures has been presented by Hilson and Pope [6].

Embedding strength is non-unique for any given specimen of timber but is dependent upon several factors, such as size, cross-sectional shape and surface condition of

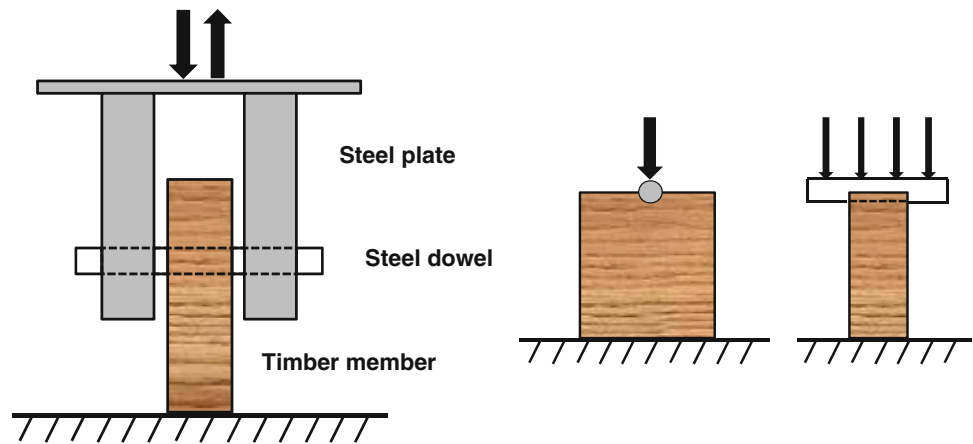
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**Fig. 1** Schematic illustrations of embedding test from EC (*left*) and ASTM (*right*)



fastener, orientation of fastener with respect to timber grain, degree of initial contact between fastener and wood [5]. To study all possible variations of those factors, the experimental way would be very time consuming. There is, therefore, a need to develop a numerical approach to investigate embedding strength more effectively [7].

In the last decade, some 2D finite element (FE) models have been proposed [8–10]. These models can be efficient to simulate the embedding behavior with thin wood members (such as the American test). However, they are limited with long fasteners such as dowel-type connections with thick timber members and slender dowels, which are three-dimensional problems (non-uniform stress distributions across the thickness of members). Therefore, it is necessary to develop a 3D FE model to simulate the embedding behavior of timber with dowel-type fastener, in particular, for multi-fastener joints with thick timber members and slender dowels. The 3D FE models have the ability to predict the load carrying capacity of dowel timber connections as well as the 3D stress field.

The wood is anisotropic material, the compressive and tensile strengths are different even in the same direction such as the parallel or perpendicular to grain directions. The wood presents ductile compressive behavior with softening in the direction parallel to grain and with hardening in the direction perpendicular to grain [11], and brittle failure in tension and shear. Thus, an appropriate wood constitutive law is important for the simulation of the non-linear behavior of embedding characteristic. Currently, wood is popularly modeled as elasto-plastic orthotropic in compression according to the Hill yield criterion. For simplification, the elastic perfectly plastic behavior has been adopted in some models [12–15]. However, the accurate prediction requires considering material hardening or softening [16, 17].

The progressive failure of timber occurs in the loading process resulting from brittle behavior in tension and shear. Few models have taken into account the contribution of tension or shear in the wood failure [10, 18–20]. It has long

been suspected that stresses in principal directions influence each other and therefore affect material failure. Especially for fibrous materials, stress interactions may change failure mode and failure stress. Multiaxial stresses must be considered in two- or three-dimensional structural elements such as plates, shells or elements under combined loading [21]. Some numerical models including the Tsai–Wu failure criterion, which is based on interactive failure theory, have been developed [13, 22]. A concern exists about using the Tsai–Wu criterion due to the need to evaluate the stress interaction coefficients that are sensitive to the test methods used to evaluate biaxial strength. No recommendations exist for selecting interaction coefficients for 3D wood failure [23]. Although several failure criteria exist for wood and orthotropic materials, most are difficult to apply to 3D stress fields.

It should be noted that few 3D FE models representing the behavior of timber connections are available in the literature. This paper represents a contribution in this field. A suitable material model for wood will allow engineer to predict embedding behavior in numerous applications without the reliance on extensive empirical tests. In this study, timber in compression is modeled as elasto-plastic material with hardening according to Hill yield criterion, and brittle behavior in tension and shear is modeled using the modified Hill failure criterion. Good correlation has been obtained between the experimental results and the FE simulations.

## Constitutive modeling

### Elasto-plastic behavior of wood in compression

The timber properties are orthotropic with identical properties in radial and tangential directions. This combined direction is referred to as perpendicular to grain ( $\perp$ ) while the longitudinal direction is referred to as parallel to grain ( $\parallel$ ). Wood has a cellular structure that is made up of

lumens and cell walls. Due to this structure, wood cells buckle and collapse under compressive loads. In compression parallel to grain, clear wood shows plastic soft-

version of the von Mises yield criterion to take into account the anisotropy of the materials. Its stress potential can be expressed as follows:

$$\left\{ \begin{aligned} \bar{\sigma} &= \left[ a_1(\sigma_y - \sigma_z)^2 + a_2(\sigma_z - \sigma_x)^2 + a_3(\sigma_x - \sigma_y)^2 + 3a_4\tau_{xz}^2 + 3a_5\tau_{yz}^2 + 3a_6\tau_{xy}^2 \right]^{1/2} / \sqrt{2} \\ a_1 &= \frac{2}{f_{c,90}^2} - \frac{1}{f_{c,0}^2}; a_2 = a_3 = \frac{1}{f_{c,0}^2}; a_4 = a_5 = a_6 = \frac{2}{3f_v^2} \end{aligned} \right. \quad (1)$$

ening, in compression perpendicular to grain, it shows ductile behavior with extended yielding plateau followed by significant hardening after the cell walls had collapsed into the lumens and the wood densified [11].

However, for the glued laminated timber, this plastic softening phenomenon in the longitudinal direction is not significant, it can be approximately regarded as elastic perfectly plastic [24]. In the direction perpendicular to grain, the behavior of glulam in compression can be represented by a bi-linear elasto-plastic law including hardening [24]. The simplified bi-linear stress–strain curve is shown in Fig. 2, where the hardening slope (tan  $\theta$ ) is equal to 10 % of  $E_{90}$ .

The theory of plasticity is a procedure by a set of constitutive equations for a multi-axial stress state. This is accomplished on three basic properties: a yield criterion, a flow rule, and a hardening rule. Hill’s yield criterion (stress potentials) [25] has been adopted to simulate anisotropic plastic behavior of the glulam. This criterion is a generalized

The hypothesis of associated plasticity is considered. Thus, the Hill yield criterion is used as a plastic flow law. The relationship between the plastic strain increment and the stress increment is given by:

$$d\varepsilon_p = d\lambda \frac{\partial \bar{\sigma}}{\partial \sigma} \quad (2)$$

where  $d\lambda$  is the plastic multiplier. In this study, the isotropic hardening rule was adopted as in [17, 26], which assumes that the center of the yield surface remains stationary in the stress space, but that the size (radius) of the yield surface expands, due to hardening.

$$H = \frac{d\bar{\sigma}}{d\varepsilon_p} \quad (3)$$

$H$  is the plastic modulus of the effective stress–effective strain diagram, which can be derived with the following set of equations [10]:

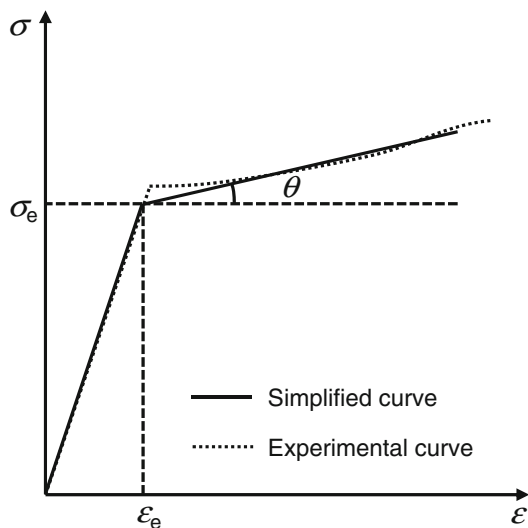
$$\sigma_c^2 - f_c^2 = \frac{E_p}{H} (k^2 - k_0^2) \quad (4)$$

$$E_p = \frac{EE_T}{E - E_T} \quad (5)$$

$k_0$  and  $k$  are the initial and updated effective yield stresses, respectively.  $E_p$  is the plastic modulus, and  $E_T$  is the tangent modulus of the stress–strain curve. Depending on the chosen value of  $H$ , perfect plasticity or hardening can be modeled.

#### Brittle failure behavior in tension and shear

In shear and tension, timber essentially exhibits behavior with brittle character which is represented by the modified Hill failure criterion. The Hill failure criterion was reformulated in such a way that tension and shear stresses which lead to brittle failure modes were considered. It can be expressed by Eq. (6).



**Fig. 2** Simplified bi-linear stress ( $\sigma$ )–strain( $\varepsilon$ ) curve in compression perpendicular to grain

$$\frac{\sigma_x^2}{f_{t,0}^2} + \frac{\sigma_y^2}{f_{t,90}^2} + \frac{\sigma_z^2}{f_{t,90}^2} - \frac{\sigma_x\sigma_y}{f_{t,0}^2} - \frac{\sigma_x\sigma_z}{f_{t,90}^2} - \left(\frac{2}{f_{t,90}^2} - \frac{1}{f_{t,0}^2}\right)\sigma_y\sigma_z + \frac{\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2}{f_v^2} = 1 \tag{6}$$

Where  $\sigma_i$  and  $\tau_{ij}$  are the stresses in timber,  $f_{t,0}$  and  $f_{t,90}$  are the tensile strength parallel and perpendicular to grain,  $f_{c,0}$  and  $f_{c,90}$  are the compressive strength parallel and perpendicular to grain,  $f_v$  is the shear strength of timber.

Numerically, in this criterion, the progressive failure is simulated through a reduction of the material modulus to represent the damage evolution in timber. Thus, when the criterion is reached at an integration point, the elastic modulus in the direction parallel to grain  $E_0$  and the modulus in the direction perpendicular to grain  $E_{90}$ , are set equal to 10 % of their initial values. Hence, a kind of damage evolution in timber is considered.

### Numerical applications

#### Embedding test

To validate the developed FE model, embedding tests were carried out with various orientations of fastener with respect to timber grain according to ASTM standard. The configuration and geometry of the specimens are shown in Fig. 3 and Table 1.

#### Model description

3D FE model is developed using the MARC.MSC software package [27]. The geometry of the FE model, based on

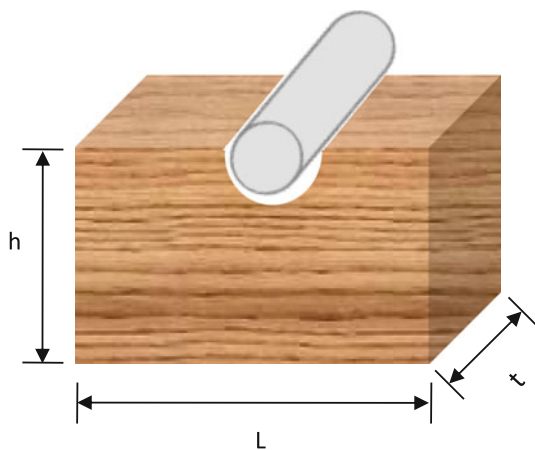


Fig. 3 Configuration of embedding test

Table 1 Dimensions of specimens

$\alpha$ (°)	$d$ (mm)	$L$ (mm)	$h$ (mm)	$t$ (mm)
0	16	96	112	40
45	16	160	88	40
90	16	224	64	40

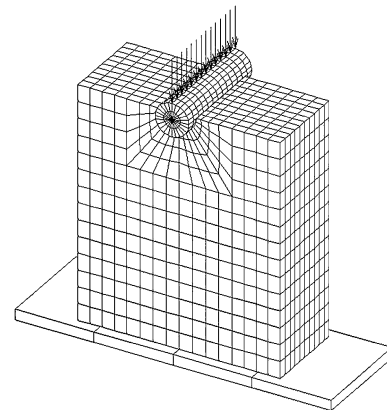


Fig. 4 Finite element mesh for the embedding test

Table 2 Timber properties used in the model

$E_0$ (MPa)	$E_{90}$ (MPa)	$G_{mean}$ (MPa)	$\nu_{TR} = \nu_{LT}$	$\nu_{RL}$
11600	390	750	0.41	0.02

8-noded hexahedral elements, is shown in Fig. 4. The model includes three parts: timber member, stiff steel dowel and plate at support.

#### Material properties

The glulam used in the tests corresponds to the resistance class GL28h in accordance with standard “EN 1194”. Its measured mean density  $\rho_{mean}$  is equal to 453 kg/m<sup>3</sup> and the moisture content  $h_{mean}$  is equal to 11 %. The values of the mechanical elastic parameters used are given in Table 2.

In this study, timber tensile strength (parallel and perpendicular to grain) and shear strength values are considered:  $f_{t,0} = 19.8$ ,  $f_{t,90} = 0.48$  and  $f_v = 3.24$  MPa. These mean values are obtained from the characteristic values using the coefficient 1.2. Considering a normal distribution, this equivalence corresponds approximately to a coefficient of variation equal to 10 %. Mean values of compressive strength are determined by test according to European standard:  $f_{c,0} = 39$  and  $f_{c,90} = 5.74$  MPa. As the deformation on the dowel is within the elastic range and also very small, therefore, the dowel is considered as an elastic material.

Load, boundary and contact conditions

The loads are introduced using controlled displacements applied on the nodes of the steel dowel with a management of the contact condition between the steel dowel and the timber member. Contact was modeled using the direct constraint method in MSC.Marc. The method requires the definition of the “contact body” that potentially may come in contact with the other body. Contact bodies can simply be the physical bodies themselves (e.g. timber, dowel and steel plate). In this method, when a node of a body contacts another body, a multipoint constraint is imposed. This constraint allows the contacting node to slide on the contacted segment. In this way, a contacting node is forced to be on the contacted segment. During the iteration procedure, a node can slide from one segment to another, changing the retained nodes associated with the constraint. A node is considered sliding off a contacted segment if it passes the end of the segment over a distance more than the contact tolerance.

Contact may be developed with friction based on the Coulomb criterion. The method allows no movement until the friction force is reached. After that, the movement is initiated and the friction forces remain constant. The friction coefficient between the timber member and stiff steel plate was set equal to 0.2 [28]. Considering surface condition of dowel, the friction coefficient between the dowel and timber was set equal to 0.3, which can be considered as the limit value between the smooth and rough surface dowel [29].

Model validation

The 3D FE models are validated on the basis of a comparison between the embedding strength-displacement curves given by FE models and those from tests. Three series of experiments were conducted, and four specimens were tested in each series. The specimens were labeled as

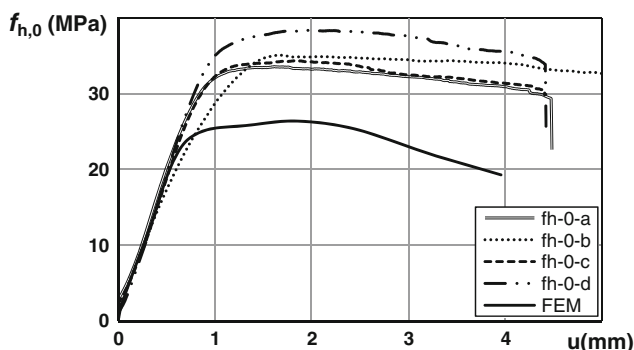


Fig. 5 Comparison between numerical and experimental embedding strength-displacement curves under loading parallel to grain

fh-x-a,b,c,d: “x” represented the angle between the loading direction and the direction of grain; “a,b,c,d” represented the specimen identification. The predicted embedding strength-displacement curve under loading parallel to grain is presented in Fig. 5. Though the predicted embedding strength is lower than the experimental ones, the model shows a similar tendency with the experimental curves. The underestimate of the embedding strength can be explained by the fact that the FE model does not take into account the material densification effect underneath the dowel. In fact, due to densification, wood underneath the dowel should have higher density and modulus.

Figures 6 and 7 show the reasonable prediction of the embedding strength-displacement curves under loading at 45° from the longitudinal direction and under loading perpendicular to grain. The differences between numerical and experimental curves, on the hardening slopes in the initial plasticity range, can be explained by the simplification of bi-linear compression behavior with hardening in the direction perpendicular to grain. In fact, after a linear elastic part, the crushing strength of wood fibers is reached. Then, a certain kind of plateau occurs and, at higher strains, the curve increases as the local density of wood increases (Fig. 2).

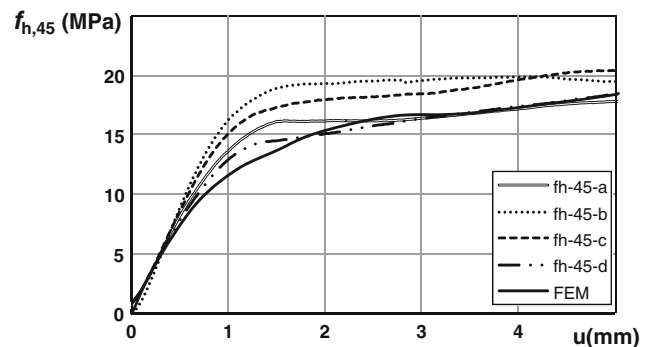


Fig. 6 Comparison between numerical and experimental embedding strength-displacement curves under the loading at 45° from the longitudinal direction

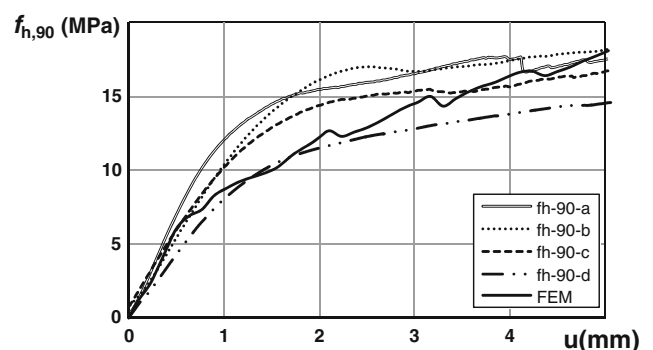
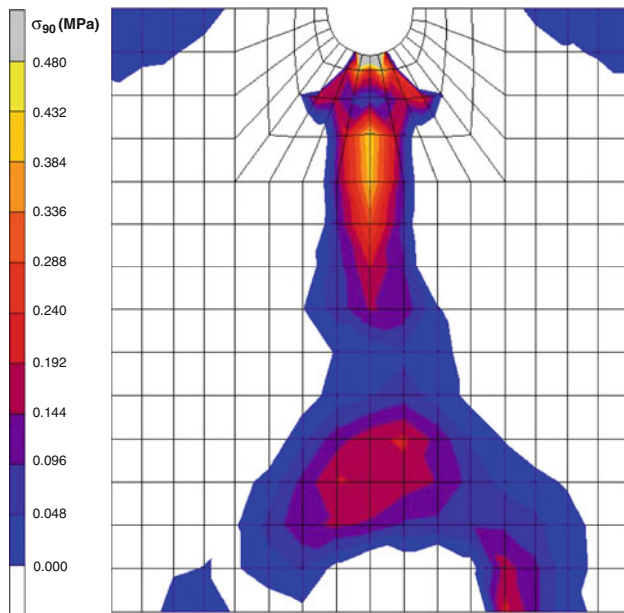
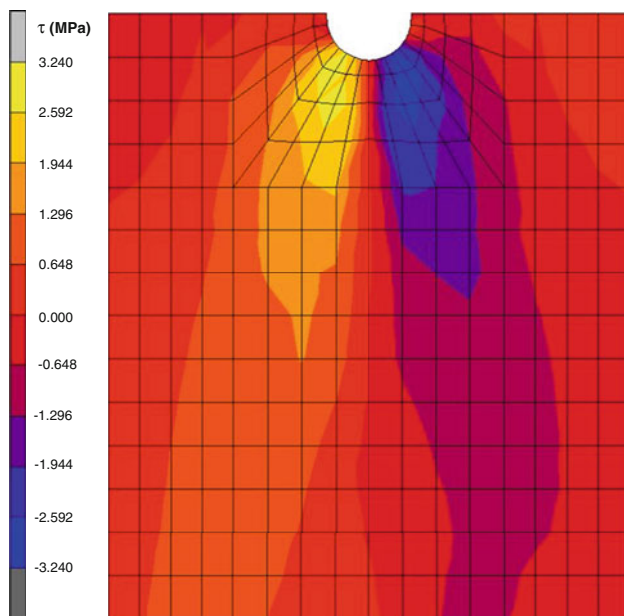


Fig. 7 Comparison between numerical and experimental embedding strength-displacement curves under loading perpendicular to grain





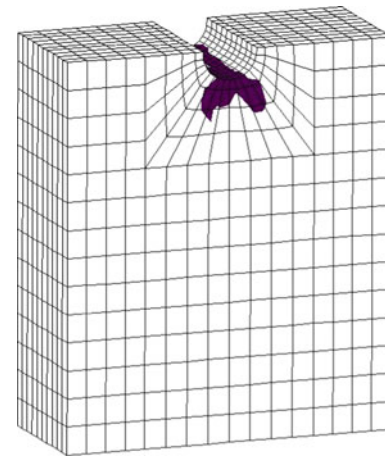
**Fig. 8** Perpendicular to grain tensile stress distribution at 5 % diameter offset load parallel to grain



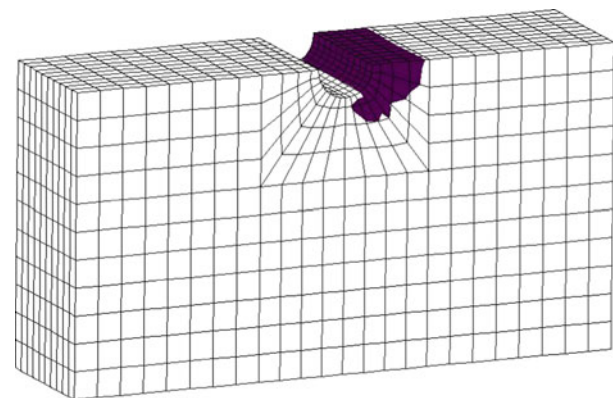
**Fig. 9** Shear stress distribution at 5 % diameter offset load parallel to grain

### Stress analysis

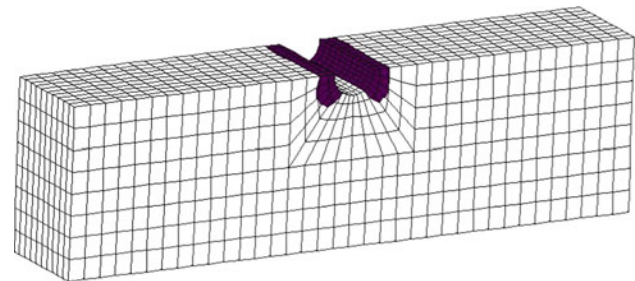
For tests with specimens loaded in the direction parallel to grain, the failure occurred prematurely by splitting parallel to grain. The brittle failure is related to tensile stresses perpendicular to grain and shear stresses. Figures 8 and 9 present the tensile and shear stress distributions in timber at 5 % diameter offset load parallel to grain. The crack



Load direction 0°



Load direction 45°



Load direction 90°

**Fig. 10** Contour plot of the zones where the failure index is reached parallel to grain appeared and propagated under the dowel during the test, which is in accordance with the observed stress contours.

The failure index of the modified Hill criterion based on the stresses' interaction provided by the numerical model is used to evaluate the potential brittle failure position. Figure 10 shows the zone where the failure criterion is reached at 5 % diameter offset load. Under loading parallel to grain, the zone with high values of failure index is

located under dowel hole, which is consistent with the location of initial crack. For loading at 45° from the longitudinal direction, the shear failure is close to the dowel hole and along the direction parallel to grain, which is consistent with the numerical observation. Under loading perpendicular to grain, the main failure is the embedding failure, due to the crushing of wood fibers, the splitting parallel to grain occurred on both sides of the dowel hole. The brittle failure can be predicted by this model.

## Conclusion

A 3D FE model for glued laminated timber behavior is presented and successfully applied to predict the dowel type embedding strength. The proposed model describes the material non-linearity of timber in terms of plastic behavior in compression and brittle failure in tension and shear. Particularly for compression perpendicular to grain, the model can be used to simulate the strain hardening of timber. The developed model is an improvement on previous wood constitutive models. It can be helpful to design and analyze various timber connections.

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