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Non-linear analysis of dowelled timber connections: a new approach for embedding modelling

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ABSTRACT

A finite element modelling is developed to analyse the behaviour of timber connections taking into account the plastic behaviour of the timber beneath the fasteners. The local non linearities control the stiffness and the load-carrying capacity of the timber joints. It results in interaction effects on the stress states in the timber and the load distribution among the fasteners that can lead to brittle failure modes such as the block shear failure.

This paper presents a new approach based on the development of a pseudo three-dimensional model for the timber in the vicinity of the fasteners. According to the observed behaviour, this finite element model was developed to describe the geometrical and mechanical non-linear behaviours at the micro-scale of the wood beneath the fasteners. Considering the orthotropic behaviour of the timber, the timber around the fasteners is modelled as a structure made up of elementary finite elements. The model accounts also for the friction, the contact and the various irreversible deformations which appear within the timber. An analysis of the embedding behaviour is carried out for three species: spruce, hem-fir and iroko. The comparison of experimental and simulated results shows that this new approach provides a good approximation. An additional sensibility analysis calibrates the model efficiency for coupling the fastener deformation and the timber stresses in the analysis of timber connections.

KEYWORDS

Non linear analysis - Dowelled timber connection - Finite-element method - Contact.

1 Introduction

The dowelled connections are the main fastening technique used in timber structures. Facing the actual architectural trends, timber-to-timber connections are mainly replaced by connections using slotted-in steel plates. In this case, better aesthetical appearance and greater fire safety is obtained. According to the actual worldwide design rules [1,2], the calculation of mechanical timber joints is based upon the Johansen's yield model [3]. Considering elastic-plastic behaviour of the components, the main assumption of this approach is that no brittle failure occurs. However, recent studies [4, 5, 6] show that brittle failure mainly governs the load-carrying capacity of the connections when using slotted in steel plates. In regard to these results, the design criteria of the timber joints need to be re-examined to take into account all the potential failure modes.

In this objective, the load-slip response of the connections has to be modelled considering the interaction effects on the timber stresses in the joint area. Several approaches based on the fracture mechanic were conducted recently [7]. They allow good prediction of the load-carrying capacity of the joint. A second approach is often related to a finite element beam-foundation model which considers the embedding behaviour of the timber and the bending of the fastener [8, 9, 10]. This approach leads to accurate prediction for ductile failure. But, failure is almost brittle for common joints. Due to the anisotropy of the timber and the composite nature of the connections, accurate modelling is not well established in the whole range of the load-slip behaviour. Furthermore, the analysis at the structural scale requires knowledge not only at the failure level but in the whole range of the joint behaviour.

This paper presents the first stage for a general joint model related to the load transfer between the timber material and the fasteners. Actually, modelling timber joints with the finite element method is frequently faced to the difficulties of taking into account the elastic plastic behaviour of the wood beneath the fasteners [11]. The local crushing phenomena are no longer in accordance with the assumptions of the continuous material theory. Based on a phenomenological analysis, the present approach considers the local wood crushing as the collapse of a structure [12]. This scheme aimed to investigate the three-dimensional behaviour of the joint considering only the properties of an orthotropic material such as the wood in tension, compression and shear. Calibration and sensitivity analysis complete the study with experiments done for three species: hem-fir, Douglas-fir and iroko.

2 Phenomenological analysis

The load-carrying behaviour of the dowel type fasteners is mainly dependent on the geometry, the plastic moment of the fastener and the embedding properties of the wood. The embedment behaviour is related to the capability of the wood to support the forces applied by a rigid body with a circular section. An embedding test with cylindrical or spherical body (figure 1) shows that the large deformation capacity of the wood is largely influenced by stress interaction. It is of main importance to take into account the failure modes of the wood at the local level and to describe the rigidity of the connections at the structural level.

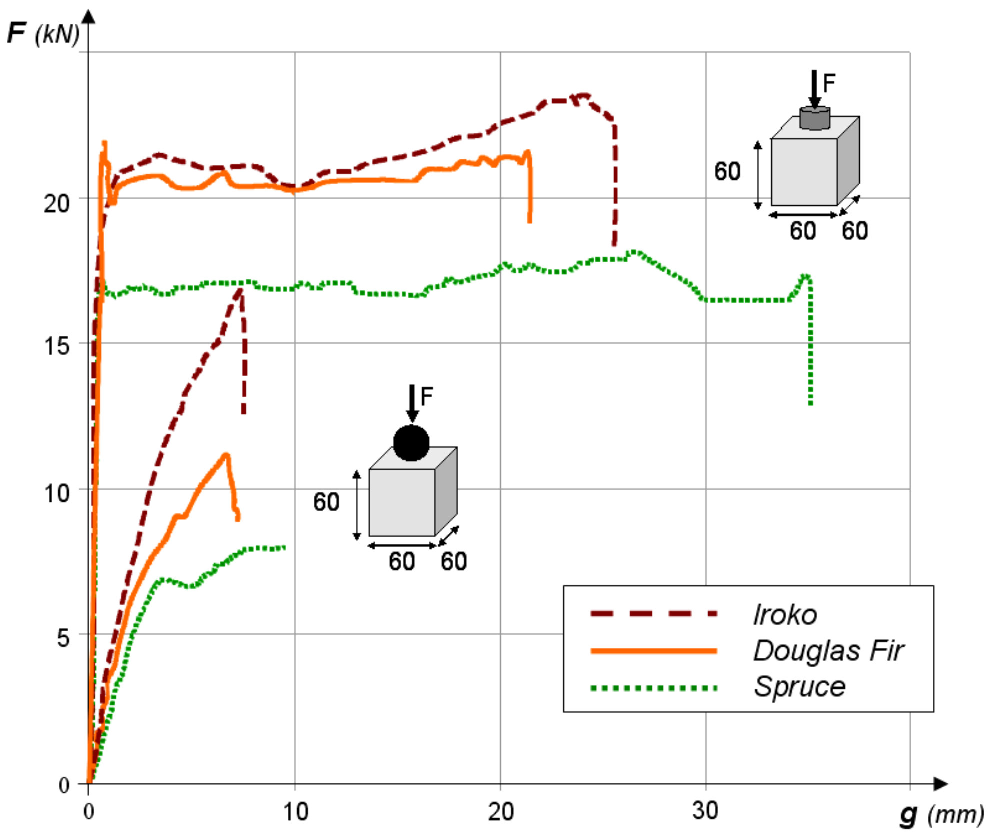


Figure 1: Embedding tests with cylindrical or spherical steel element for different timber species.

For all direction of loading, it shall be distinguished a zone beneath the fastener and the lateral parts which exhibit various modes of behaviour. In any case, the central part is stressed in the direction of the load and adherence effect is developed depending on the friction between the dowel and the timber [6]. For the lateral parts, they tend to flow around the dowel if the load is parallel to the grain (figure 2-a). When the direction of the load is perpendicular to the grain, many cracks appear parallel to the grain (figure 2-b).

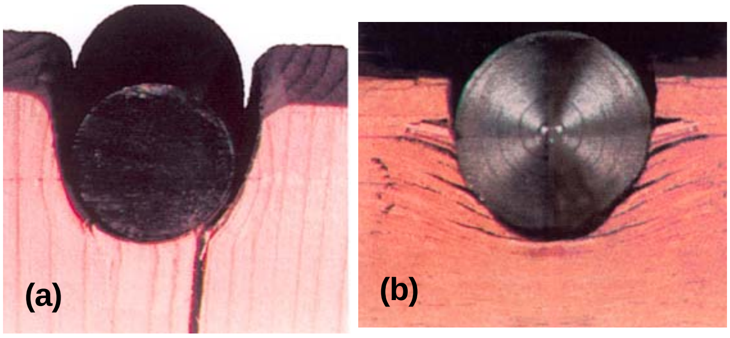


Figure 2: Embedment failures for a dowel of 18mm in diameter: a) parallel to the grain (spruce), b) perpendicular to the grain (iroko).

Thus, the yield level of embedment depends mainly on the the ductility of the wood in compression and the possible development of material discontinuities. Considering the wood as a continuous anisotropic material, the effects of the stress-strain interactions appear difficult to model [9].Qualitatively, these observations illustrate the importance of the shear behaviour of the wood on these phenomena.

In the first approach, the modelling of the timber embedment is developed with the assumption of independent behaviours of the material, i.e. behaviours in compression, tension parallel or perpendicular to the grain, and in shear are uncoupled.

3 Finite element modelling

At the scale of the fastener, the micro-structure of the timber (fibres and internal cohesion) has a predominant effect on the local failure. In other words, the local structure has a role as important as the anisotropic properties themselves. Then, the modelling approach retained is that the geometrical and the mechanical non linearity of the timber are represented by the collapse of an equivalent structure in the vicinity of the fastener.

This modelling approach was implemented in the finite element code CAST3M [13], using a specific element formed with two layers. In the first layer, bar elements in the direction of the grain take into account elastic-plastic behaviour for the compression parallel to the grain (figure 3). Joint elements are then added in a second layer. They describe the timber behaviour perpendicular to the grain which is ductile in compression and brittle in tension. In shear, the timber is usually regarded as elastic-brittle when a crack can be initiated in the grain direction. In the joint area, the cracks parallel to the grain are confined and the shear strength perpendicular to the grain is higher and more ductile. Therefore, the joint elements (Joint2D) introduce elastic-plastic behaviour in shear and a strain softening in compression perpendicular to the grain (figure 3).

The plastic deformations are limited to ε=0,20 in longitudinal or transversal compression and γ=0,20 in shear.

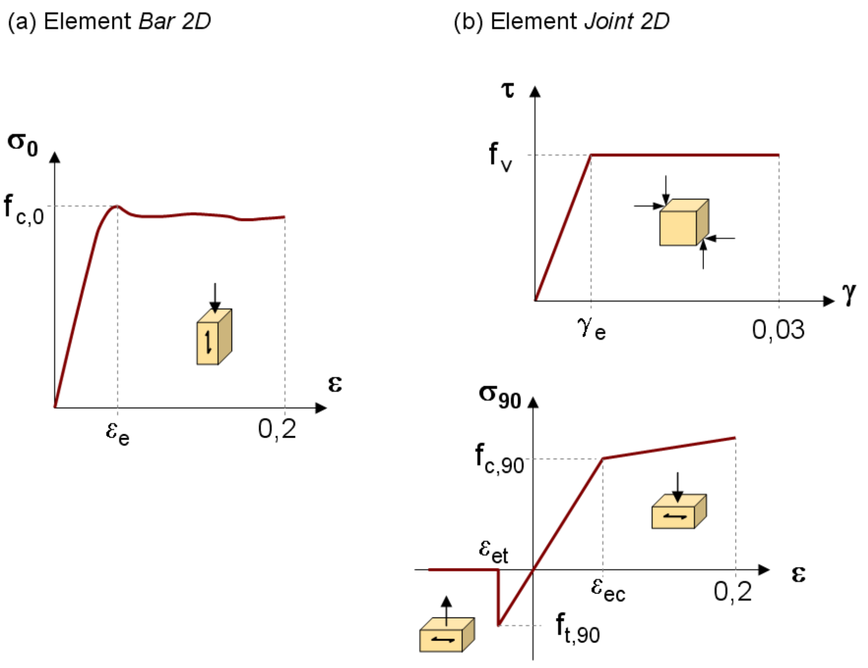


Figure 3: Constitutive behaviour of the bar 2D and joint 2D finite elements combined for local modelling of the timber.

For a timber piece of thickness E_p, this new element models an elementary volume extending over 4,5mm in the direction parallel to the grain and 2,5mm in the transverse direction (figure 4). At the local scale of the joint, the elements are used for the modelling of the timber plasticity considering that the plastic deformations are limited to the surroundings of the fastener. This area is assumed to extend over one diameter in the grain direction and half the diameter in the direction perpendicular to the grain (figure 4). Elsewhere, the timber is considered as an elastic orthotropic material.

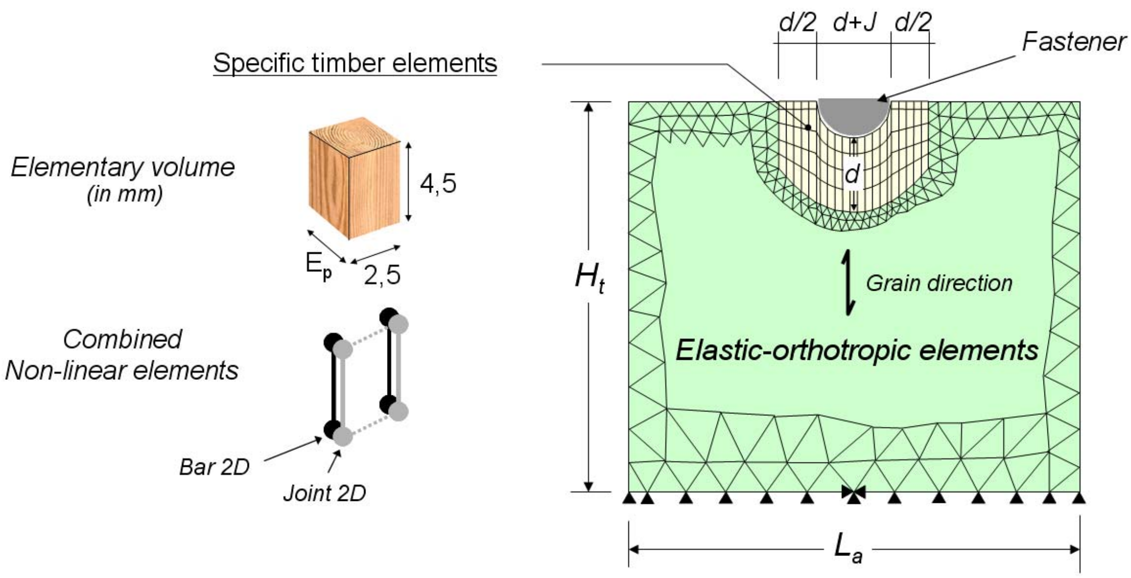


Figure 4: Finite element modelling of the fastener embedding parallel to the grain.

In order to take into account the contact and the friction effects, the interface between the timber and the fastener is modelled by stiff independent facets. Joint elements with a Mohr-Coulomb criterion link these facets to the fastener (figure 5). The contact and the gap are then modelled by additional unknown factors using Lagrange multipliers.

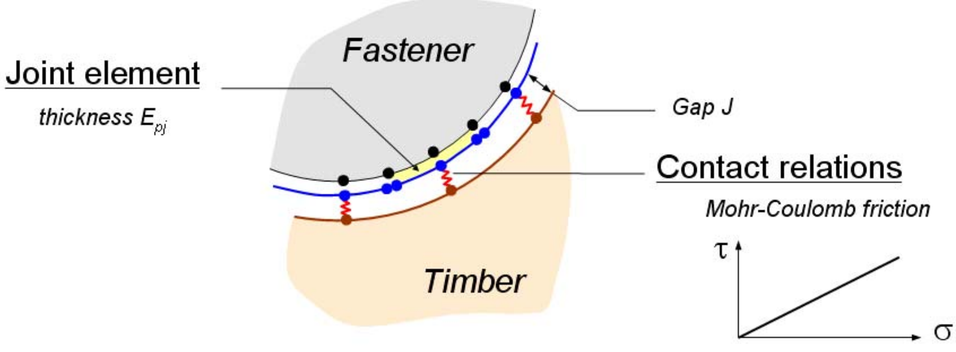


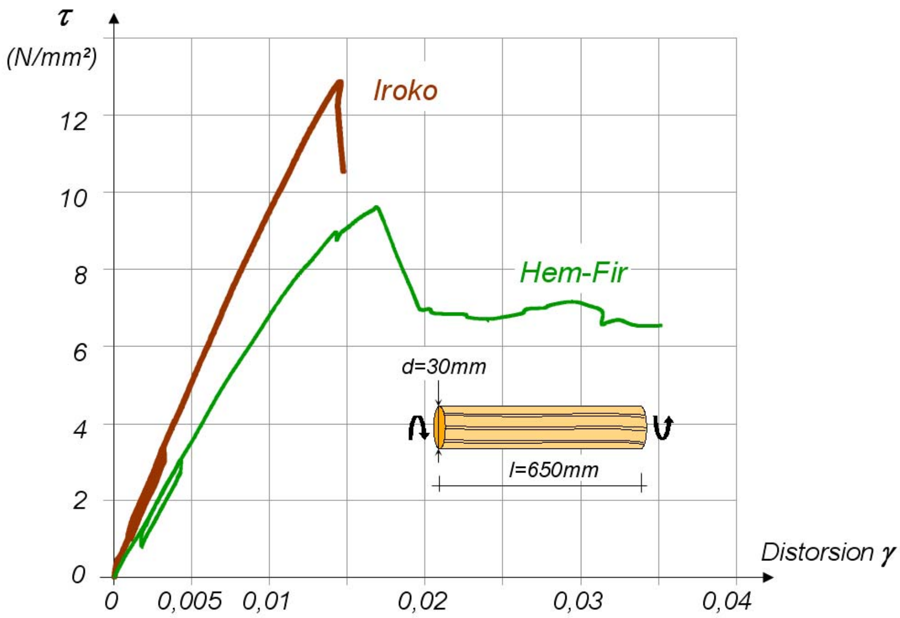
Figure 5: Interface modelling around dowel-type fastener with friction and gap.

This approach can appear simplified comparatively to a general parametric law. But, it allows taking easily into account the local properties of the timber behaviour and its discontinuities. Since the mechanism becomes as important as the thresholds of failure, simpler criteria can be considered.

4 Numerical results and discussion

For the validation of this local modelling of the timber, two glued-laminated species were considered: the Hem-Fir and the Iroko. First, a model is developed to simulate the embedding behaviour of dowelled fasteners of diameter d equal to 18mm.

The strength in compression strength parallel ($f_{c,0}$) and perpendicular to the grain ($f_{c,90}$), the shear modulus G and the shear strength f_v were defined from experiments. The tests were conducted on small specimens in confined compression and in torsion. The mean values of the mechanical properties were evaluated from 5 replications. Figure 5 shows the average behaviour observed. In compression, the yield limit is reached by the local buckling of the wood cells. Beyond, the timber exhibits large plastic deformations up to the hardening threshold.



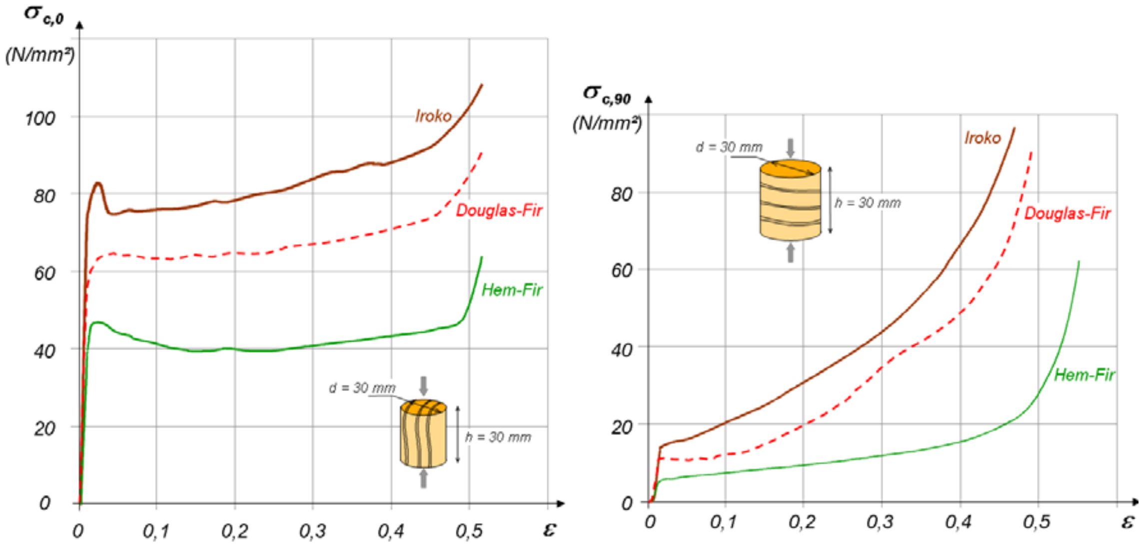


Figure 5: Material behaviour in torsion and in compression.

Other material properties were obtained from the literature. The table 1 gives the mean values considered in the model.

Specie	$f_{c,0}$ N/mm²	$f_{c,90}$ N/mm²	$f_{t,90}$ N/mm²	f_v N/mm²	E_0 N/mm²	E_{90} N/mm²	ν	ρ kg/m³	$E_{90,pl}$ N/mm²	G N/mm²
Hem-Fir	48,1	4,9	1,9	8,28	11000	518	0,41	437	22	590
Iroko	83,1	13,6	3,4	13,3	16000	1412	0,43	637	134	990

Table 1. Mechanical properties of the timber species used in the model.

Comparatively to the results of embedding tests, a parametric study is achieved for the Iroko specie. In the directions parallel and perpendicular to the grain, this analysis examined the effect of the main parameters such as the friction, the hole clearance and the material strengths.

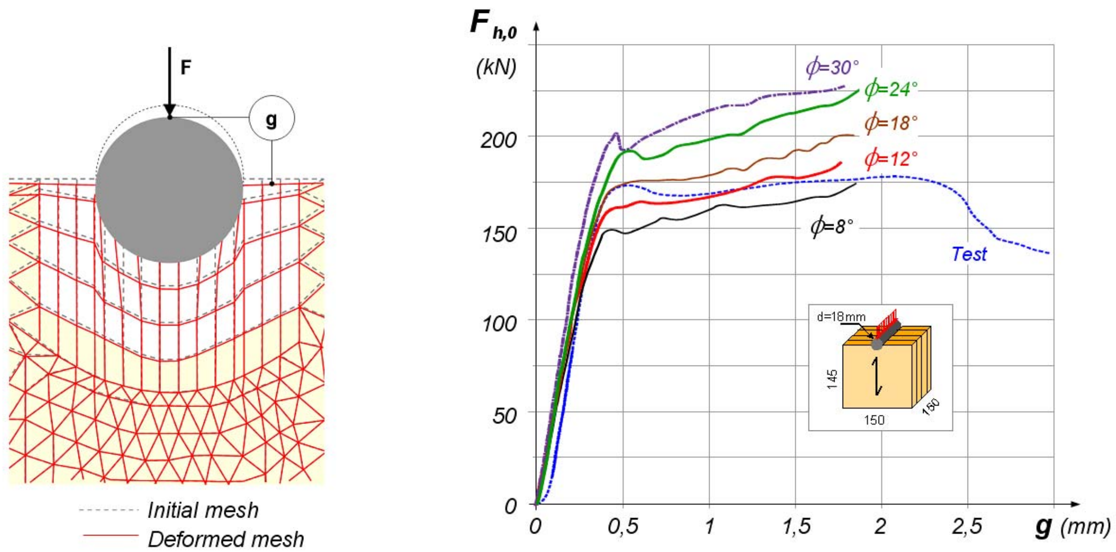


Figure 6: Effect of the friction on the embedding parallel to the grain of the Iroko.

As shown on the figure 6, the frictional contact between the dowel and the timber affects mainly the yield level. As the friction decrease, larger transverse deformations are developed. As the timber wraps around the dowel, larger stresses are obtained in compression perpendicular to the grain and in shear. In the range of the calculations, the predicted yield level of embedding parallel to the grain varies about 33%. Considering the value commonly used (ϕ=18°) [14], the ratio between the mean test value and the model is about 1,12.

For the dowel-type fasteners, an important parameter is related to the permissible hole clearance which varies from 0 (nails, dowels) to 1 mm (bolts). In this range, the model results give an estimated variation of 20% for the embedding strength in both directions. Figure 7 shows the variation of the maximum stresses beneath the fastener and at the end member. The embedding capacity is reduced about 16% for hole clearance J ranging from 0 to 0,5 mm. Considering the local stresses, the maximum shear stress is 40% lower while the tension perpendicular to the grain remains nearly constant. For the same load-carrying capacity, these results confirms the brittleness of the joints when the hole clearance increased.

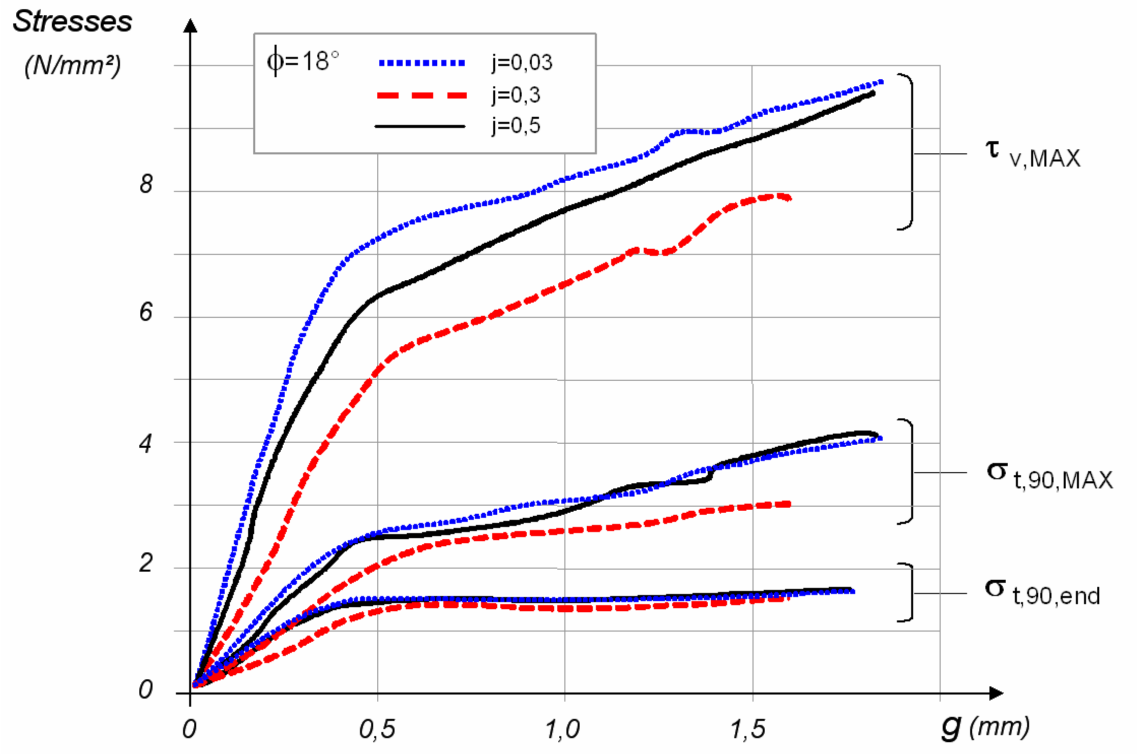


Figure 7: Effect of the gap on the shear and tension perpendicular to the grain stresses.

Furthermore, this analysis is completed about the effect of the material properties. The change of the orthotropic properties of the timber directly influences the stress and strain states beneath the fastener. The capacity of plastic deformation is mainly dependent on the timber behaviour in compression perpendicular to the grain and in shear. As shown on figure 8, the shear strength affects largely the embedding behaviour perpendicular to the grain. In the longitudinal direction, a variation of 5% is observed for change of 40% in the shear strength.

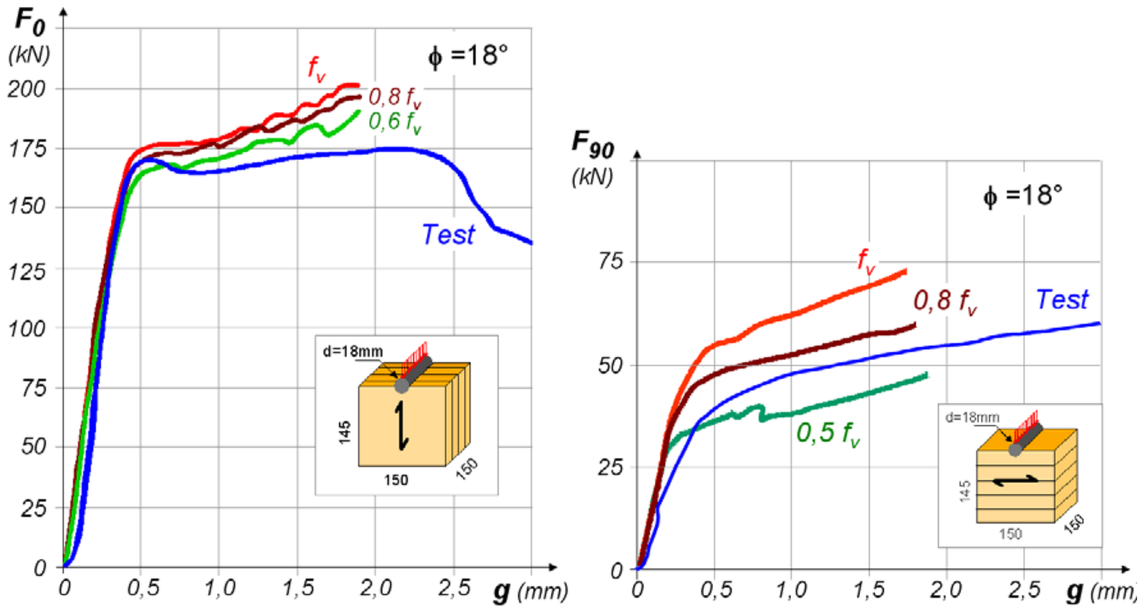


Figure 8: Influence of the shear strength on the embedding behaviour parallel and perpendicular to the grain for the Iroko.

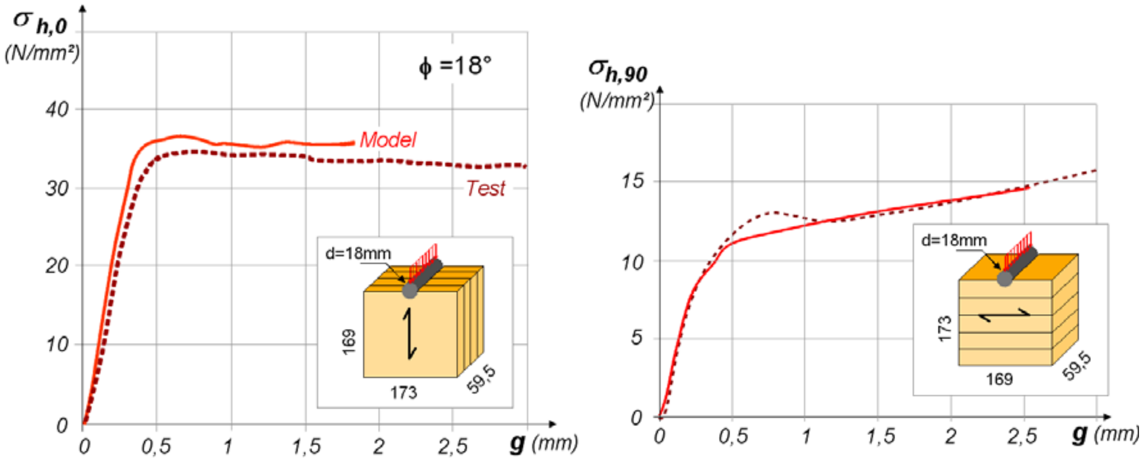


Figure 9: Comparison of the experimental and simulated results for the Hem-Fir.

Considering the Hem-Fir specimens, the model results (ϕ=18° and J=0,1mm) are in good agreement with the experiments. The anisotropic nature of the wood structure is less stratified and is characterised by a ratio $f_{c,90}/f_V$=0,6 (≈1,0 for the Iroko). For this specie, the macroscopic structure is more closed to the model which emphasised the behaviour in shear.

5 Conclusion

The stiffness and the load-carrying capacity of the timber connections are governed by the plastic deformations of the timber under the fasteners. A finite element model is proposed to approach the embedding behaviour of the wood. In the surrounding of the fasteners, the geometrical and mechanical nonlinearities are modelled combining bar and joint elements together with contact element at the interface of the fastener. Away from the fasteners, the timber is modelled as an orthotropic linear material.

Considering the material properties obtained from experiments in compression and in torsion and completed from the literature, an extensive parametric analysis was achieved for glued laminated Iroko and Hem-Fir. It was found that the shear strength and the friction coefficient could affect significantly the prediction. The influence is increased for brittle material such as the Iroko. The results for Hem-fir, for which the properties are more adequately defined, a good agreement was found between numerical and experimental results.

This study demonstrates the applicability of the proposed model to predict the plastic behaviour of the timber beneath the fasteners. It offers a more realistic alternative for the analysis of the behaviour of the timber joints as the modelling of the stiffness and the load-carrying capacity is effective. Then, the joint behaviour could be modelled using this embedment model along the fasteners to take into account the bending of the fastener in combination with a two dimensional model of the timber elements. This new approach will allow us to define a failure criterion for the timber connections considering the static and cinematic interactions in the joint area.

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