European COST Action FP1402

“Basis of structural timber design – from research to standards”

Short-Term Scientific Mission report

“Works on Different Numerical modelling Approach to Predict the Load Distribution in Timber Joints”

by

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1. Introduction and motivation

The timber construction is an ancient art of building structures. Over the centuries, the technique has been perfected to produce an art called traditional carpentry. This way of building strives to make transit as much as possible the loads applied to the structures by traction and compression to limit the deformations. Initially there were few requirements in terms of deformation which could increase the quality of the building. For centuries, the knowledge gained through experience has been enabled to produce well executed joints and the implementation of dry wood but also to help carpenters to build rigid structures without sophisticated calculations. In the last century, manufacturing processes have made it possible to have timber construction elements of larger dimensions and thus allow the construction of remarkable structures. In the last version of the European code for the design of timber structure (EN 1995-1-1) [1], it seemed important to its drafters to propose design formulas to estimate the stiffness of joints to be in adequacy with the sizing of modern structures. Aware of the technical jump that had to be crossed, the proposed rules remained simple. Today, they become insufficient to respond to a present-day challenge which is to erect high-rise wooden buildings. In the same time, the resistant capacity of dowelled timber joints is no longer determined by empirical formulas, but it is based on the Yield Analysis Theory proposed by Johansen [2]. However, this methodology introduced in EN 1995-1-1 shows its limits for complex joints even though many improvements have been made since its introduction. In parallel with these analytical approaches, the advent of computing has made it possible to develop simple numerical calculation methods Foschi [3], Hirai [4]. These nonlinear approaches have remained unused until now because of their complex implementation and their high running time but today it is able to help engineers and fill the gaps of the EN 1995-1-1 [1]. The approach is to consider the fastener as an elastoplastic beam on a nonlinear foundation, Sawata and Yasumura [5], Hochreiner et al. [6]. This method is called BOF for Beam-On-Foundation. That is the first part of this report which is the first objective of the STSM.

The second part of the report discuss about experimental investigation about compression and shear interaction of the wood which is the second objective of the STSM.

2. Beam-On-Foundation modelling

2.1. Introduction

The complexity in the local deformation and stress state in wood close to the dowel suggests using a simpler phenomenological approach to describe the embedment behaviour. Thus, beam-on-foundation approaches have been developed (see Figure 1), where nonlinear springs are used to model the contact between wood and steel dowel [7-8], by making use of mathematical functions for the relative displacement-embedment load behaviour (see [3-4]). In most of these equations, the parameters can be related to physical properties derived from uniaxial embedment tests. The simplest approach would be to assume linear tangents with a continuous intermediate nonlinear transition.

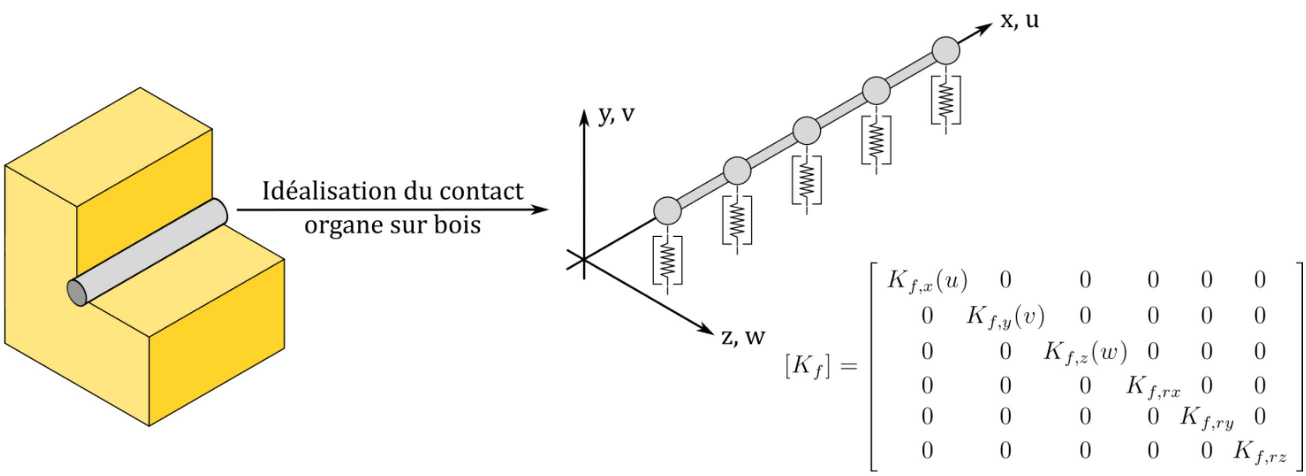


Figure 1 : Picture about principles of the BOF modelling.

In a first hand of the next part, we described the principles assumptions of the BOF modelling. And then, we compared the numerical results with the EYM of the Eurocode 5.

2.2. Principles

In this part, we showed some important parameters about the efficiency of the BOF modelling. Some of this parameter sensitivity has been already found in the literature.

2.2.1. Contact dowel/timber

The most significant parameter of the BOF modelling is the mathematical function used to describe the embedment behaviour. Some examples and explanations are described in the paper [9]. For the work of this short-term scientific mission, we chose to use only one mathematical function, the one which defined by Sauvat [10] in this thesis. The equation of this function is described below:

$$K_f(u) = -c_k \times [\arctan((f_k u + d_k)^{e_k} + a_k) + b_k]$$

The parameters of the Sauvat function can be linked with physical parameters of embedment:

$$b_k = \frac{K_{f,el} \times \frac{\pi}{2} - K_{f,pl} \times \arctan(a_k)}{K_{f,pl} - K_{f,el}} \quad \text{and} \quad c_k = \frac{-K_{f,el}}{\arctan(a_k) - b_k}$$

With:

$K_{f,el}$ and $K_{f,pl}$ respectively the foundation modulus in the elastic and plastic areas (in N/mm^3).

The other mathematical parameters could be chosen by an empirical approach to fit experimental curves of embedment tests. For this work the following values were used:

$$a_k = 2, d_k = 0 \quad \text{and} \quad e_k = 4$$

The last parameter f_k enables to define the rate of the embedment strength. For the moment this parameter is not linked with the other mathematical and physical parameters. However, by using the EC 5 equation for calculate f_h, it is possible to define some values for f_k. This point will be described below in the paragraph 2.3.1.

2.2.2. Contact dowel/steel

The modelling of the contact between the dowel and the steel plate, in case of steel-to-timber connection, is quite easier than dowel-to-timber contact. For this work we used rigid elements.

2.2.3. Discretization

The discretization of the embedment behaviour, i.e., the number of spring elements along the dowel, depends on the side member thickness. Hirai [4] proposed a law to determine the number of springs depending on the thickness of the wood and the dowel diameter. If the ratio between the timber thickness and the dowel diameter is less than ten then nine springs are enough to modelized the embedment. If the ratio is more than ten, it is necessary to use more springs and check the influence of the number of springs on the numerical results.

2.2.4. Step sensitivity

Numerical simulation is performed in elastic calculation, which is incremental. At each increment of calculation, the matrix system resulting from the finite element method is solved. As the wood and steel matrices of the joints have elastic behaviours, the choice of the value of the computation step has no influence, because at each increment the material properties remain identical. However, the nonlinear behaviour of the joint is integrated by modifying after each computation step the foundation moduli of the springs and the elastic moduli of the beam elements constituting the dowel according to the phenomenological models used. The choice of the value of the computation step has in this case a significant importance on the results of the simulation (see Figure 2).

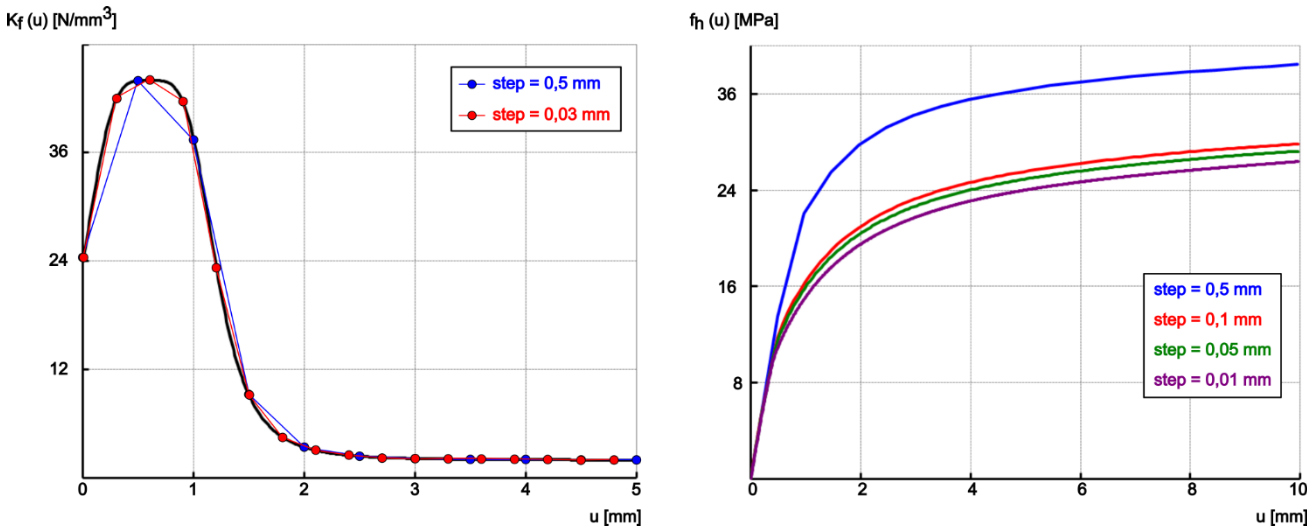


Figure 2 : Influence of the step size on the numerical results.

2.2.5. Steel behaviour

The dowel itself is modelized by one-dimensional beam elements, which makes it possible to reduce the number of elements compared to a three-dimensional model. An elastic-plastic material behaviour is assigned to these beam elements.

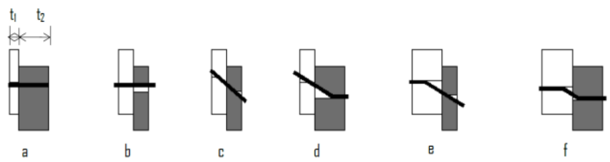
2.3. Comparison with EYM

In this work, the comparison was only made for connections subjected by a normal force parallel to the grain. To check the efficiency of the BOF method to describe the single-dowel behaviour in this case of loading, all the parameters of the strength capacities EYM formulas have been chosen to maximize the possibilities of the method and guarantee all failure modes. This set of data is explained in the next paragraph, then the comparison of the strength capacity is explained, finally the comparison of the stiffness connection is exposed.

2.3.1. Data base set

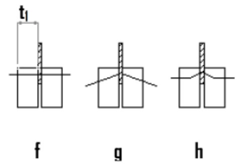
To compare the BOF modelling results with the EYM, a set of parameters was chosen from EYM equations where the stochastic coefficients have been deleted (see below):

Timber-to-timber connection



$$F_{v,R} = min \begin{cases} f_h t d \quad (a-b) \\ \dfrac{f_h t d}{2}\left(\sqrt{10}-2\right) \quad (c) \\ \dfrac{f_h t d}{3}\left(2\sqrt{1+\dfrac{3M_{y,R}}{f_h d t^2}}-1\right) \quad (d-e) \\ \sqrt{2M_{y,R} f_h d} \quad (f) \end{cases}$$

Steel-to-timber connection



$$F_{v,R} = min \begin{cases} f_h t d \quad (f) \\ f_h t d\left(\sqrt{2+\dfrac{4M_{y,R}}{f_h d t^2}}-1\right) \quad (g) \\ \sqrt{2M_{y,R} f_h d} \quad (h) \end{cases}$$

In the equations above, some parameters have been simplified compare to the standard version. In fact, in this work we restrained the case where the two timber members have the same thickness ($t = t_1 = t_2$) and the same embedment strength $\left(f_{h,1} = f_{h,2} \Rightarrow \beta = 1\right)$.

The yield moment formula of the EC 5 for steel dowel was given with stochastic coefficient. To get rid of these coefficients, we used the equation derived from the mechanic:

$$M_{y,Rk} = 0.3 f_{u,k} d^{2.6} \Rightarrow M_{y,R} = \frac{f_y d^3}{6}$$

The embedment behaviour has been simplified to define the value of the foundation modulus in the elastic and plastic areas. In fact, we supposed that the transition of the plastic behaviour appeared at an embedment of one millimetre and the general behaviour was elastoplastic where the plastic value was given by the formula of the EC 5 for embedment in softwood:

$$f_h = 0.082(1 - 0.01d)\rho$$

List of parameters:

- ρ: density of wood member;
- f_y: elastic limit of the dowel;
- d: dowel diameter;
- t: thickness of wood member;
- t_{steel}: thickness of the steel plate.

Set of parameters:

- $\rho \in \{350kg/m^3; 420kg/m^3\}$;
- $f_y = 240MPa$;
- $d \in \{8mm; 12mm; 16mm; 20mm; 24mm\}$;
- $t \in \{10mm; 20mm; 40mm; 60mm; 80mm; 100mm; 140mm; 200mm\}$;
- $t_{steel} = d$.

In the Table 1 below, all the parameters used to define the nonlinear foundation for the numerical tests with the BOF modelling are listed. To define $K_{f,el}$, $K_{f,pl}$ and f_k a regression has been made to minimize the gap between the Sauvat curve of the foundation and the bilinear approach in the elastic and plastic parts.

Table 1 : Parameters used to define the nonlinear foundation of the BOF modelling.

	$\rho = 350kg/m^3$					$\rho = 420kg/m^3$				
$d(mm)$	8	12	16	20	24	8	12	16	20	24
$f_h(MPa)$	26.40	25.26	24.11	22.96	21.81	31.68	30.31	28.93	27.55	26.17
$K_{f,el}(N/mm^3)$	26.91	25.74	24.57	23.4	22.23	32.3	30.9	29.5	28.08	26.7
$K_{f,pl}(N/mm^3)$	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
f_k	1.381	1.381	1.381	1.381	1.381	1.381	1.381	1.382	1.381	1.382

2.3.2. Strength capacity

To compare the strength capacity of the analytic results of EC 5 and numerical results of BOF an assumption was made about the rate of the relative displacement of the connection members. In fact, the embedment strength used in the numerical tests was given by the EC 5 equation which the strength value is defined at five millimetres of embedment. So, we decided to compare the analytical and numerical results for a connection slip of five millimetres.

The figures below (Figure 3 and Figure 4) illustrate the comparison between analytical and numerical results. For the timber-to-timber connections, the results are quite efficient with a relative gap less than 5%. However, for the steel-to-timber connections, the results have a more important relative gap between 5% and 10%.

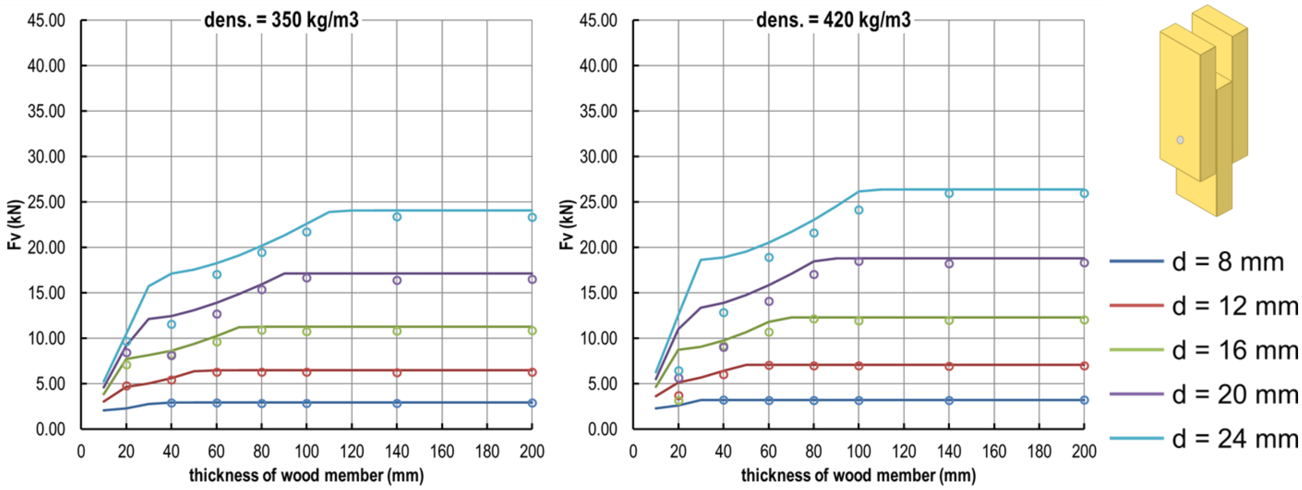


Figure 3 : Comparison of BOF modelling results with EYM for timber-to-timber connections.

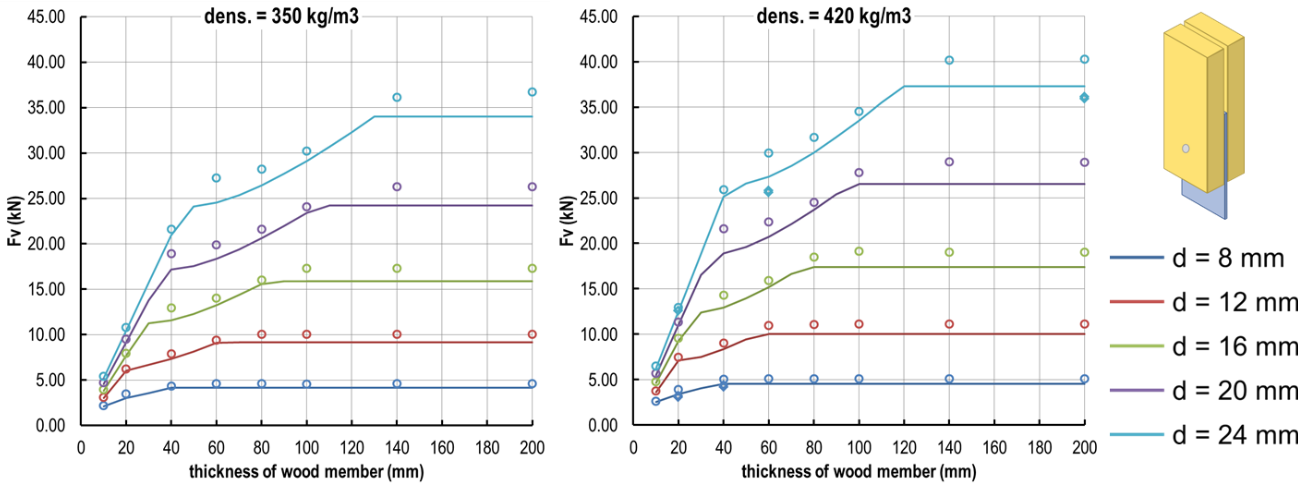


Figure 4 : Comparison of BOF modelling results with EYM for steel-to-timber connections.

2.3.3. Stiffness

From the EC 5, only one empirical formula is given to calculate the stiffness of a connection:

$$K_{ser} = \frac{\rho_m^{1.5} d}{23}$$

This formula doesn't integrate the thickness of timber members, or the stiffness of the steel plate and the failure modes. So, it seemed interesting to compare the stiffness formula of the EC 5 with the stiffness calculates with the BOF modelling approach. This comparison is illustrated on the two charts of the Figure 5

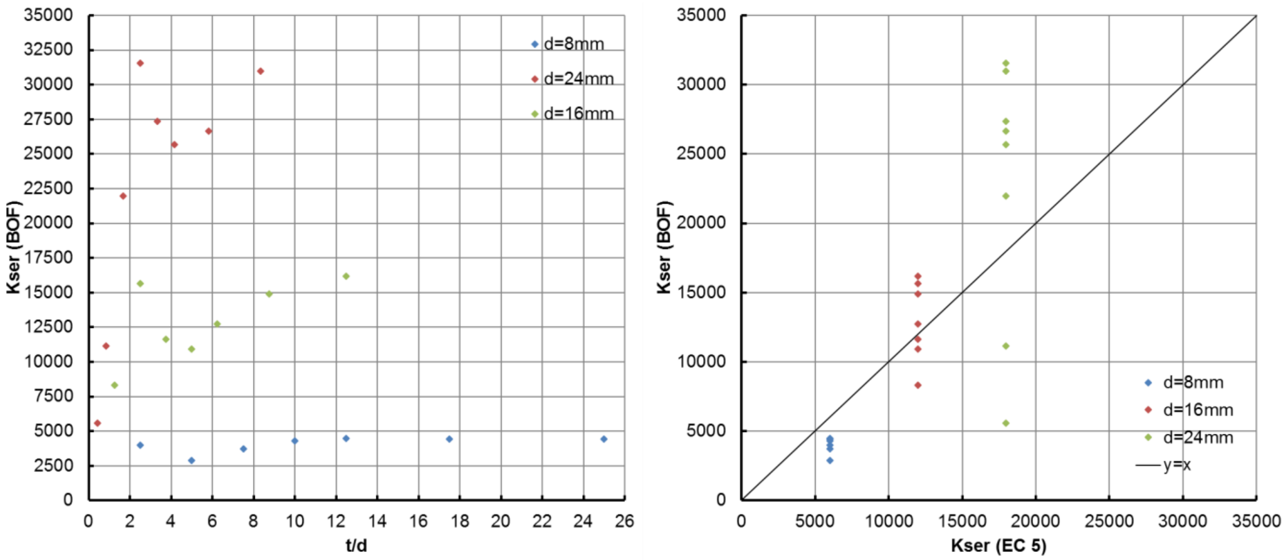


Figure 5 : Comparison of BOF modelling results for stiffness with the EC 5 formula.

As expected, the results show that the thickness of the timber members is a significant parameter for determining the stiffness of a connection. That's why a numerical approach with a BOF modelling could be a good response to tackle the lack in this part of the EC 5.

3. Hybrid modelling

3.1. Introduction

At the scale of few millimetres, the wood has an alternating repetitive layer structure linked to its growth. So, in a ring, the early wood has a very different density of the late wood. That's why, the behaviour of the wood can be assimilated as the composition of a porous material in transversal directions and a rigid material in the longitudinal direction. This idea had been developed in the PhD theses of Pascal Toussaint [11] and Iman Tavakoli [12] with the finite element analysis software Abaqus. In this type of modelling, called hybrid modelling, the behaviour of wood perpendicular to the grain is considered by mechanical model of foam (crushable foam from Abaqus) and the behaviour parallel to the grain by an elastoplastic beam (see Figure 6).

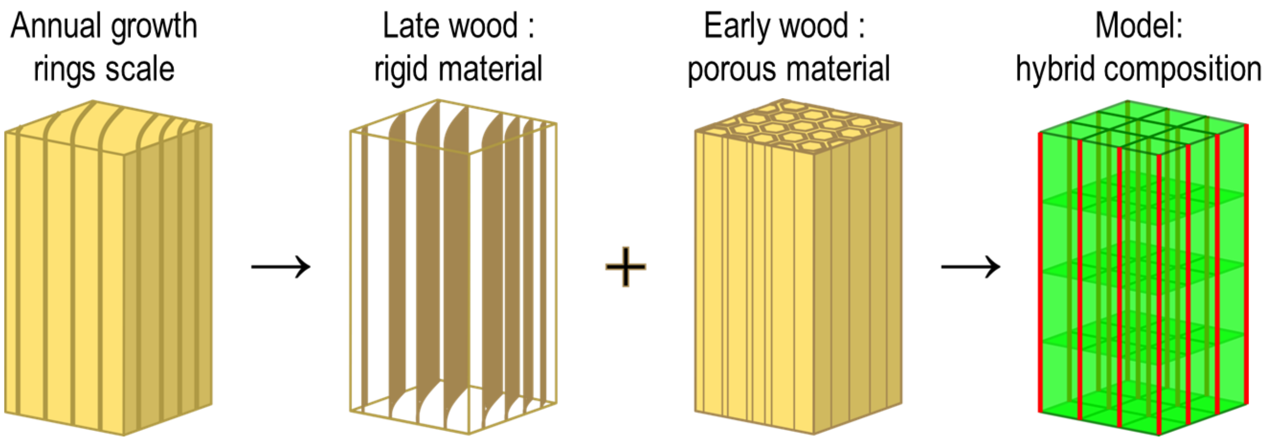


Figure 6 : Principles of the hybrid modelling developped by Toussaint and Tavakoli [11-12].

This hybrid approach has shown to be able to simulate efficiently the embedment behaviour of wood in 2D (see Figure 7). However, in their studies, this model could not be extended to 3D. that's why, one of the motivation of the STSM at the Linnæus University is to work on the hybrid model described above to extend the model to 3D, thanks to the host institutes abilities with the software Abaqus and mechanics of materials. Moreover, the disposal of a biaxial testing machine at the Linnaeus University made it possible to carry out tests on wood specimens with two independently applied loads at the same time, namely compression and shear force. This stress combination is most important for calculation of stresses in the embedment behaviour of wood. The results of those biaxial tests will improve in the future the finite element formulation for the foam (see Figure 8) included in the hybrid model.

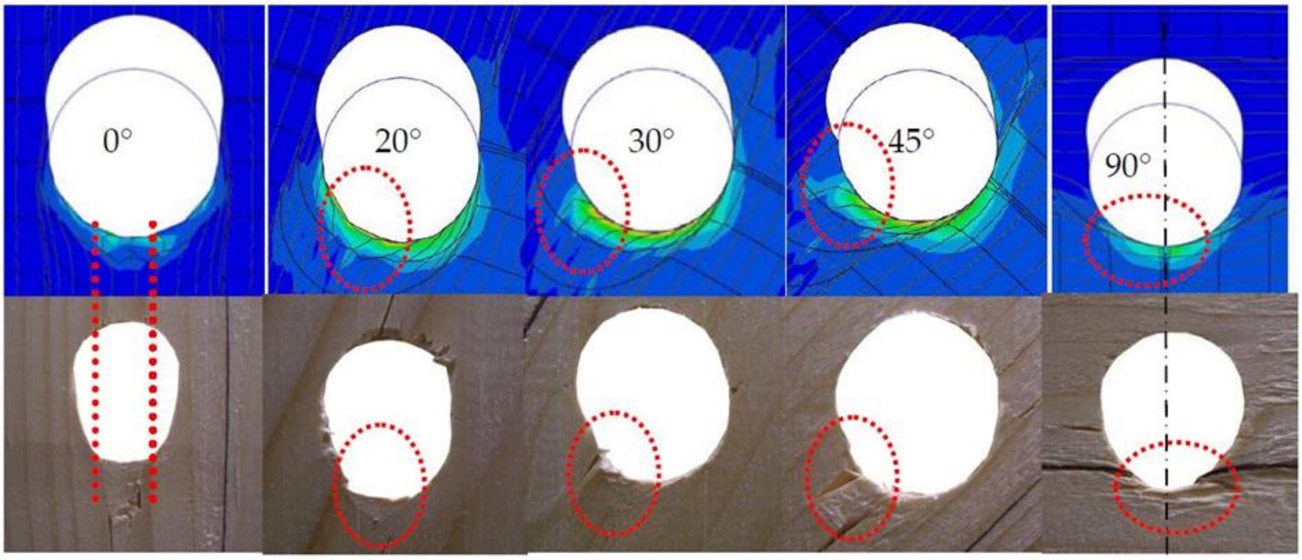


Figure 7 : Comparison between embedment tests at different load-to-grain angle and its numerical simulations for the hybrid modelling developped by Toussaint and Tavakoli [11-12].

Yield surface : $F(p,q) = \sqrt{q^2 + \alpha^2\left(p - \frac{p_c - p_t}{2}\right)^2} - \alpha\left(p - \frac{p_c + p_t}{2}\right)$ Ellipse in hydrostatic and deviatoric stresses plane

Volumetric hardenning model :

p_c^0 : yield stress in hydrostatic compression
$p_t = p_t^0$: yield stress in hydrostatic tension
σ_c^0 : yield stress in uniaxial compression

$$k_t = \frac{p_t}{p_c^0} \qquad k = \frac{\sigma_c^0}{p_c^0} \qquad \alpha = \frac{3k}{\sqrt{(3k_t + k)(3 - k)}}$$

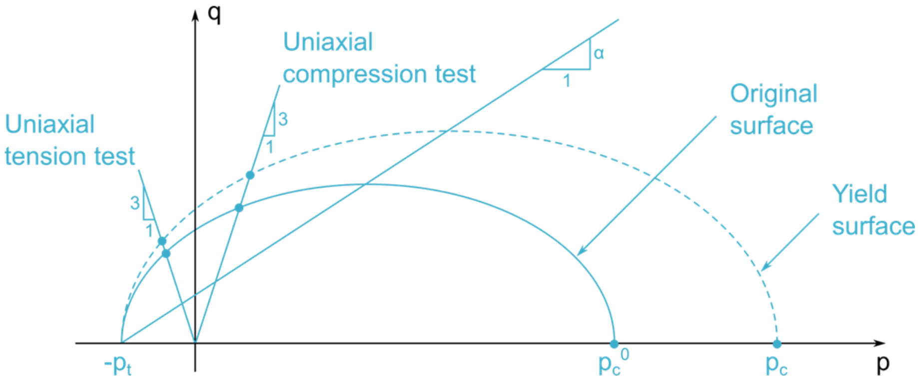


Figure 8 : Formulation of the crushable foam in Abaqus software.

3.2. Materials and methods

About thirty specimens have been realized to carry out bi-axials tests (compression parallel to the grain and shear) on softwood specimens (spruce). The sizes of the specimen are illustrated on the Figure 9 below. Due to the orthotropic symmetry of the wood, two shear planes could be considered, τ_{RL} and τ_{TL}. However, in the time of the STSM, only one shear plane was tested: τ_{RL} (see Figure 10).

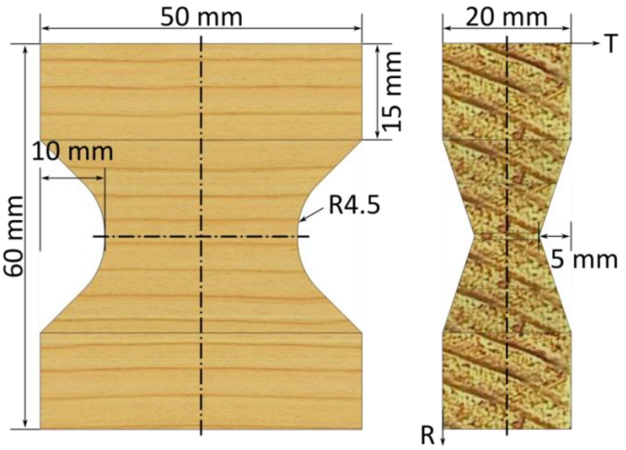


Figure 9 : Sizes of the specimen for bi-axials tests.

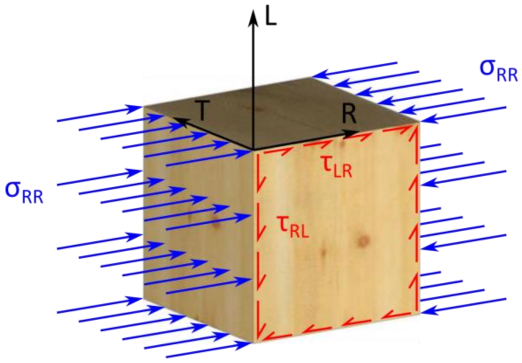


Figure 10 : Direction and applied loads on the specimens for bi-axials tests.

Before to start tests, all the specimens were stored in an environment with a relative humidity of 65 % and a temperature of 20 °C for one month. That was enabled to reach the equilibrium moisture content of the spruce which is between 11.5%-12% for that relative humidity and temperature. The density and the growth rings were measured. All the statistic values for the density and growth rings data are given in the Table 2 below.

Table 2 : Statistics values of the specimen used for the bi-axial tests.

	$Density\ (kg/m^3)$	$Growth\ rings\ (mm)$
Mean	403.28	3.26
Standard deviation	10.79	0.18
Maximal	437.68	3.75
Minimal	383.70	2.86
COV	2.68%	5.54%

To observe the influence of the load, different cycles of loading have been used:

- Pure tension tests (4 tests);
- Pure compression tests (4 tests);
- Compression (1 mm/min) + shear (1 mm/min) (5 tests);
- Compression (1 mm/min) + shear (0.8 mm/min) (3 tests);
- Compression (1.5 mm/min) + shear (0.5 mm/min) (2 tests);
- Compression (1 mm/min) + shear (0.5 mm/min) (1 test);
- Compression (600 N) + shear (3 tests);
- Compression (1.65 kN) + shear (1 test);
- Compression (1.2 kN) + shear (1 test);

Some tests were carried out with the same speed displacement for the two hydraulic jacks of the bi-axials set-up while some other tests were carried out with different speed displacement. A third cycle of loading was used where the vertical load (compression or tension) was maintained as a level defined before the test.

To measure the strain of the timber, a recording system developed by the society Aramis was used. Some painting was added on all the specimens to help the analysing of the strain (see Figure 11).

3.3. Results and discussions

Some pictures of the specimens after failure are exposed in the Figure 11 below.

Specimen Comp. + shear Pure shear Pure tension

Figure 11 : Pictures of specimens after failure for different loding.

The results of the bi-axials tests are presented in the Figure 12 below.

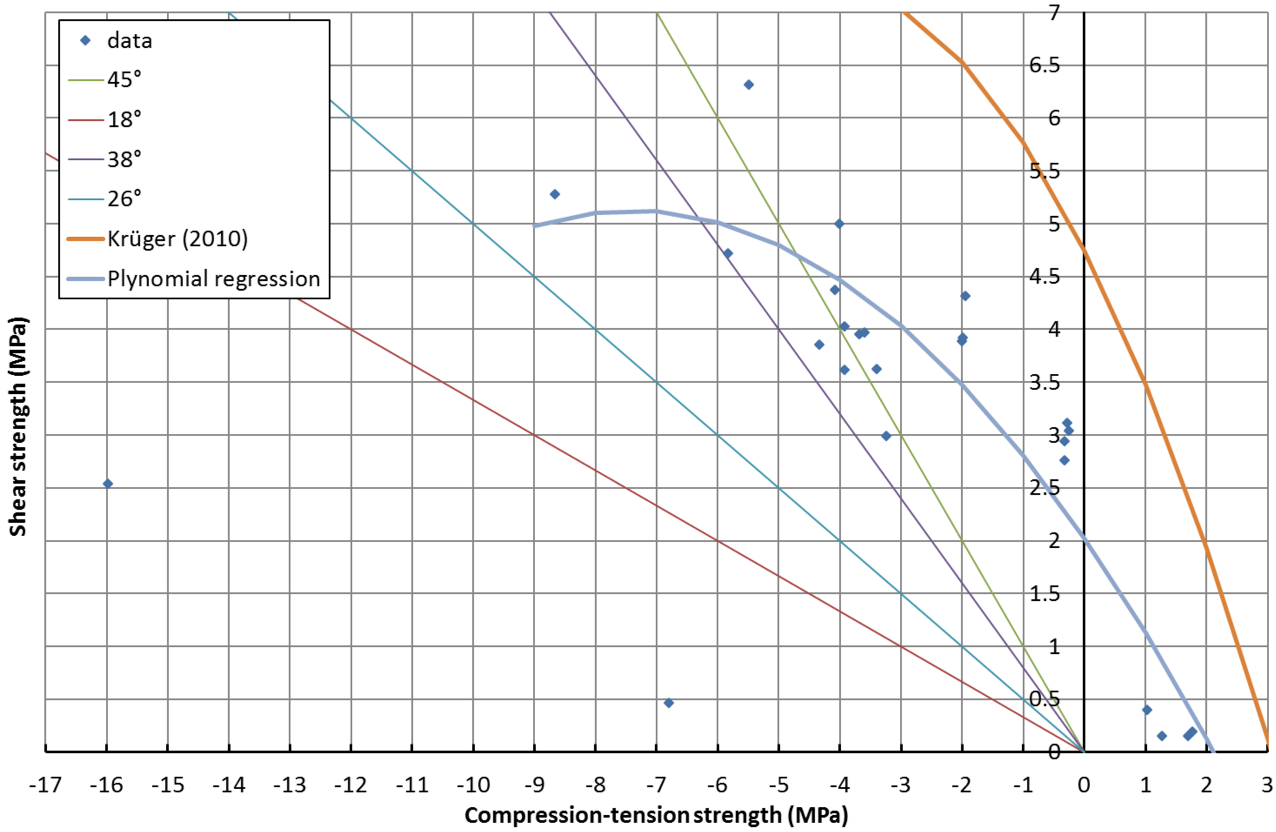


Figure 12 : Results of the bi-axials tests.

In the literature we can find work about shear and compression by Krüger [13]. the author established an empirical law linking the shear resistance and the compression/tension perpendicular to the grain.

Empirical equation of Krüger [13]:

$$f_v = 4.75 - 1.15\sigma_{RR\ or\ TT} - 0.13\sigma^2_{RR\ or\ TT}$$

The results of the Figure 12 have permitted to etablished a similar law.
Empirical equation of the STSM tests:

$$f_v = 2.02 - 0.84\sigma_{RR\ or\ TT} - 0.06\sigma^2_{RR\ or\ TT}$$

4. Conclusion, outlook

One of the objective of the STSM at the Linnæus University was to work on the comparison of the BOF modelling with the EYM of the EC 5. This comparison shows that BOF modelling could be a good alternative for design connections of timber structure. In the future the work about BOF modelling will be continued with the host Linnæus University. A paper will be presented at the INTER 2018 at Tallinn in Estonia.

During this STSM, an updating of the European Norm EN 383 methods have been discussed also to improve the analyse of embedment test curve and define better the parameter useful for the nonlinear foundation of the BOF modelling.

The second objective of the STSM was to carry out experimental investigations of the compression-shear interaction in wood to improve a hybrid modelling developed on the FEM software Abaqus. This study must be completed, this will be done in the future by the work of a PhD student from Linnæus University and the updating of the hybrid modelling will be continued by collaboration with Linnæus University and LERMAB.

Acknowledgements

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