Cost Action FP1004: Short Term Scientific Mission at Lund University
Finite element modelling of a new structural insulated panel based on CLT using Abaqus

Laurent Léoskool[a,*], Erik Serrano[b], Thierry Descamps[a]

[a] *University of Mons, Mons, Belgium*
[b] *Lund University, Lund, Sweden*

Abstract

The development of a new structural insulated panel is studied. The skins are composed of cross-laminated timber (CLT) and the insulation is non-rigid. The mechanical behaviour is preserved thanks to inclined screws that join the wood panels. This new product presents advantages: it could be used for bigger buildings; it could improve the CLT construction by a higher level of prefabrication and a reduction of the wood consumption. In order to understand the mechanical behaviour of this new product, experimental and numerical studies are carried out. The present report describes a short term scientific mission which has been carried out at Lund University in Sweden. The aim of this mission was to improve the numerical studies by a simplification of the geometries and the development of new contact interfaces between screws and CLT panels, to be able to represent the brittle behaviour of the wood. The more efficient solution uses smooth cylinders instead of real 3D models of the screws and the contact interface is treated thanks to a cohesive behaviour. A hybrid material is also created between the steel and the wood to respect the main physical properties: the bending and tensile rigidities of the screw and the failure location between the steel and the wood.

Keywords: cross-laminated timber, finite element modelling, Abaqus, assembly, screw, cohesive surface, contact interface

*University of Mons
Email address: laurent.leoskool@umons.ac.be (Laurent Léoskool)
URL: www.umons.ac.be (Laurent Léoskool)

November 28, 2014

1. Background and introduction

1.1. Proposition of a new Structural Insulated Panel with CLT

One of the main disadvantages of the cross-laminated timber concerns the insulation and the volume of wood which is used. A solution that reduces these disagreements is studied at the University of Mons (BE) [1]. It consists in the creation of a kind of SIP made of two CLT panels and an insulation between them (see Figure 1). Developing such a SIP accelerate the construction speed. Exterior facades require only the installation of a wood cladding or another type of water protection (generally, bricks in Belgium). The insulation can be blown or composed of semi-rigid panels, which allows the use of most eco-friendly materials. Assuming a good connection between the panels (local or linear connections independent of the insulation), the mechanical behaviour can be improved (reduction of the slenderness, increase of the second moment of area) and therefore the thickness of the CLT panels can be reduced. This new type of CLT panel should reduce the cost of the construction thanks to a reduction of work time and of raw material needs.

Figure 1: Structural insulated panel composed of cross-laminated timber.

1.2. Materials

For this study, cross-laminated timber panels with a thickness of about six centimetre are used. This panels are already produced by many manufacturer and are generally used for internal walls (See Table 1).

Self-tapping screws are used to connect the panels each other. Screws used to reinforce timber structures are preferable. They are constantly threated over their entire length so the distance between the panels is preserved during the screwing. These screws are already used to repair or reinforce structures, as for example in case of delamination of glulam beams. Their dimensions are available till one metre and the common diameters are nine or thirteen millimetre (see Table 2).

Wood wool insulation is used between the panels. Its thermal conductivity is equal to about $0,04 W/m.K$ as for fiberglass or rock wool. Its manufacture is simple and ecologic.

Table 1: Product features of the solid wood slab for mechanical actions perpendicular to the plane [2].

Modulus of elasticity Parallel to the grain of the boards Perpendicular to the grain of the boards	 $12000MPa$ $370MPa$
Shear modulus Parallel to the grain of the boards Perpendicular to the grain of the boards	 $690MPa$ $50MPa$
Bending strength parallel to the grain of the boards	$24MPa$
Tensile strength parallel to the grain of the boards	$0,12MPa$
Compressive strength perpendicular to the grain of the boards	$2,7MPa$
Shear Strength Parallel to the grain of the boards Perpendicular to the grain of the boards	 $2,7MPa$ $1,5MPa$

Table 2: Characteristic load bearing capacities and dimensions of WR-T13 screws [3].

Characteristic yield moment	$84,6Nm$
Charecteristic tensile strength	$58400N$
Characteristic yield strength	$930MPa$
Characteristic withdrawal capacity parameter (perp. to grain)	$12,9N/mm^2$
Inner diameter	$8,5mm$
Outer diameter	$13mm$

1.3. Structure and technology

Structural insulated panels have a mechanical behaviour which can be compared with the I-beams. The wood panels have the role of the flanges and the insulation (in our case the screws) has the role of the web. So the flanges are able to resist to bending moment and the web resists to shear forces.
New SIP have to be provided with sufficient screws to be enough stiff and resist to shear forces. The screws can be positioned with different screwing angles, thereby facilitating the passage of efforts. The screw features (number of screws per square metre, screwing angle and direction, diameter and length of the screws) can be determined thanks to experimental tests and finite element models. At first, experimental tests can be done as shown in Figure 2 . The mechanical behaviour of screws can be interpreted and the failure modes determined for each configuration of screwing.
On the contrary, the number of screws per square meter have to be minimise to reduce to its minimum the thermal bridges which are created. A study have to

be done to quantify the loss of thermal efficiency.

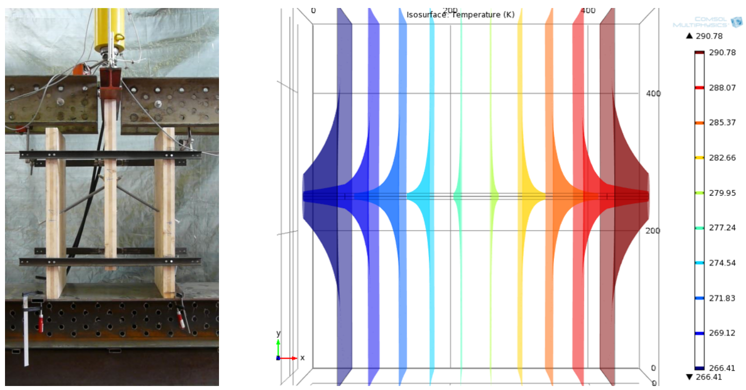

Figure 2: Studies of local mechanical behaviour (left); thermal bridges studies (right).

1.4. Experimental campaign

Different kind of samples (triumphal arches) have been studied [4]. First ones are made without gap between the panels, second ones have a gap of 18 mm and the third ones have a gap of $23cm$ between the panels. For each category, three situations are tested : with a screwing angle perpendicular to the panels ($0°$) and with screwing angles of $+30°$ and $-30°$ with regard to the perpendicular. The three situations for a gap of $18mm$ are shown in Figure 3 .The assemblies are made as triumphal arches in order to understand the behaviour of each screw depending on their screwing angle and in order to give a symmetry to the assembly. The screwing angle of $+30°$ ($-30°$) leads to a sum of shear and tension (compression) stresses.

1.5. FEM analysis

Finite element models have been established in order to approach the experimental results as close as possible [5]. The software used is Abaqus. The load bearing capacity of the assemblies is obtained from non-linear models. The calculation method which is used is Abaqus Explicit. Timber is modelled as an orthotropic material and the orientation (longitudinal, radial and tangential) respects the layout of the crossed layers of the CLT panels. The plasticity of the timber is taken into account thanks to the Hill criterion[6] [7] [8] .
In addition to the Hill criterion, a small strain hardening is applied to the nominal yield stress. The value of the strain hardening is obtained by trial and error and it allow to calibrate the non-linear behaviour with the experimental tests. This procedure allow to obtain a good correlation with the experimental without the need of complex damage laws.
Fully threated models of the screws are made thanks to a CAD program and are

Figure 3: Panels assembly with gaps of 18 mm, perpendicularly screwed (left), screwed at $+30°$ (centre), screwed at $-30°$ (right).

exported into Abaqus. The steel is considered elastic perfectly plastic. Hard contact and friction are used to assure the contact interfaces.

These kind of models gives convincing results in correlation with the experimental tests (see Figure 4). Nevertheless, the Hill criterion does not allow to differentiate the yield stresses in compression and in tension, whether they are parallel or perpendicular to the grain. Furthermore, Hill criterion is only suitable in case of ductile failure and hence, it is not efficient to model the mechanic behaviour of the timber in any situation. Furthermore, these models are very time-consuming, so simplified models have been developed with unthreaded shanks and different properties for the material interfaces (contact and friction, cohesive surfaces or tied surfaces) to be able to model more complex simulations like entire walls or floors.

2. Research plan

2.1. Project description

Hence the observations mentioned above, a short term scientific mission have been carried out at the Lund University with the main goal to reduce the computation time and make possible the appearance of brittle failure modes. This work has been done with the help of Professor Erik Serrano and the department of Structural Mechanics.

Different solutions were possible to characterize a brittle behaviour. The first idea was to use Abaqus sub-routines in order to implement the real behaviour of the timber but this solution has not been studied given the complexity of the model (anisotropic, non-linear properties and non-linear effects of large displacements) and the time which was available for this mission (1 month). The final option was to represent the brittle behaviour by a breaking of the contact interface around the screw and the ductile behaviour thanks to the Hill criterion.

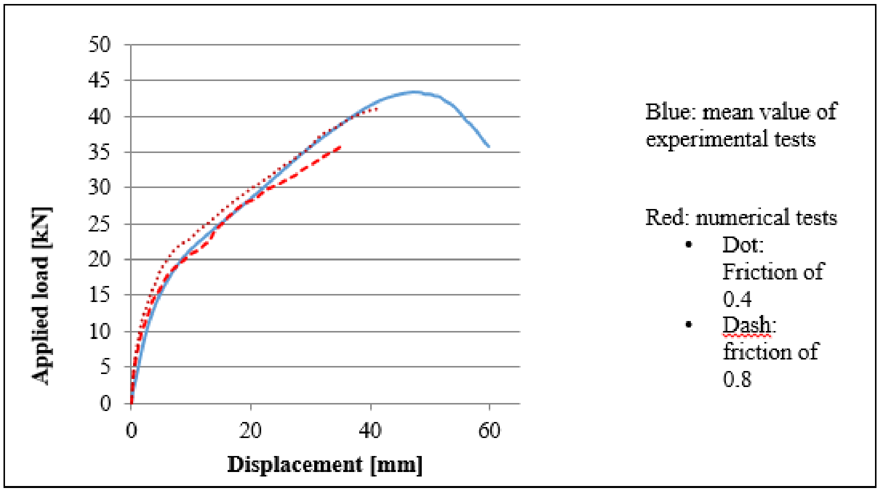

Figure 4: Numerical and experimental results for an assembly perpendicularly screwed with a gap of 18 mm, results given for 4 screws in simple shear.

Two different types of contact interfaces have been studied. The first one is governed by contact and friction and a prestress in the wood is used to allow the screw to resist even if the load is applied axially. A second method, easier to characterise but less physically realistic, is based on cohesive surfaces.

2.2. Methodology

Different types of models have been developed in order to characterise the wood behaviour as better as possible.

Pull-out test models allow to characterise the withdrawal capacity of the screws. The associated failure is generally brittle and its location is very close to the outer diameter of the screw. Two types of pull-out tests have been modelled, the classic one where it was possible to obtain a comparison the characteristic values of the screws furnished by SFS Intec [3] and a second type of model based on the experimental campaigns of Dr Robert Jockwer where it was possible to obtain correlations in terms of rigidity, strength and post-failure behaviour for perpendicularly screwed CLT panels [9] [10].

Triumphal arches with screws placed perpendicularly to the panels have been modelled. In that case, the global behaviour is mainly governed by the bending of the screws and the embedding of the wood around the screw (rotation of the screw). The failure is ductile and the Hill criterion seems to be sufficient for this purpose. Correlations are possible thanks to experimental campaigns discussed before [4].

2.2.1. Smooth 3D elements with contact and friction

Concept. Given the thread of the screw, the failure between the steel and the wood parts will be always positioned along a cylinder of a diameter of $13mm$ (outer diameter of the screw) or more. In this model, the screw is represented by a smooth shank of approximately $9mm$. This dimension is needed to obtain a good compromise between the rigidities in tension (EA) and bending (EI), a steel bar of $13mm$ would be too stiff and strong. A material (called soft material thereafter) has been conceived so as to reach the outer diameter of the screw. This material is considered perfectly elastic and relatively soft in the radial direction to minimize the stress concentrations (important impact for the Hill criterion). Properties in the longitudinal and tangential directions and for the shear properties are similar to the wood. These features are not realistic but they characterise a really complex behaviour. Indeed, this zone is a mixture of steel parts (the threads) and wood material which is compressed and crushed.
The prestress is obtained by a difference of diameters between the soft material and the wood. The hole in the wood material is considered slightly smaller (for example $12,8mm$ instead of $13mm$) and the soft material has to shrink to fit perfectly the contact surface. This way of working allows to have stresses perpendicular to the surface and by consequence, the possibility to have friction between the two surfaces even if the applied load on the screw is perfectly axial (see Figure 5).
The interface between the steel and the soft material is considered perfectly rigid.

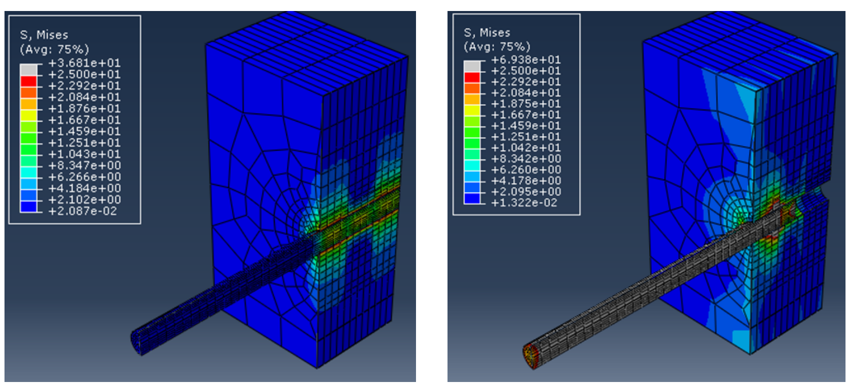

Figure 5: Pull-out model with contact, friction and prestress, before (no loading) and after failure.

Results. Results shown in Figure 6 represent pull-out tests. We can see on the left graph that a higher diameter difference between the soft material and the wood or a higher friction coefficient increases the withdrawal capacity and the rigidity of the screw. These results are given for a CLT panel which is considered perfectly elastic (without hill criterion). In this case, a model with a friction

coefficient of $0,3$ and a diameters difference of $0,1mm$ is sufficient to reach the characteristic withdrawal capacity given by the furnisher (called SFS value in the graph 2).
The Hill criterion is not needed for a pull-out test given that the failure is characterised by the contact interface. Nevertheless, this criterion have to be considered for the triumphal arch models and the aim is to have only one set of parameter for all the configurations.

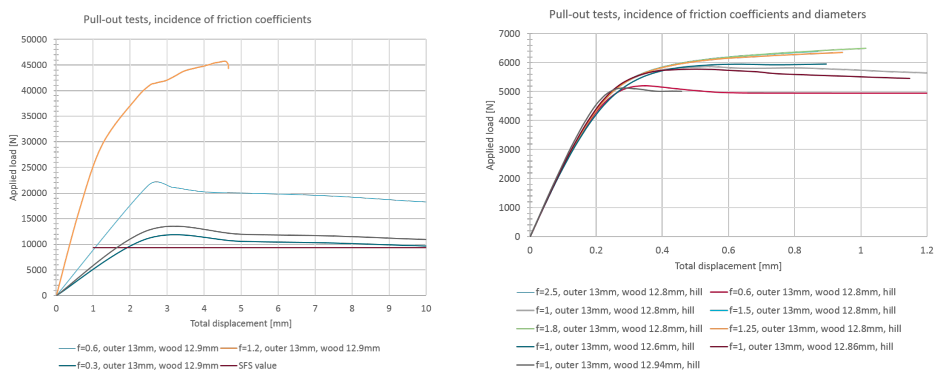

Figure 6: Results of pull-out tests with contact, friction and prestress, without hill criterion in the wood(left), with hill criterion (right).

Results in Figure 6 (right) show that the Hill criterion reduces considerably the withdrawal capacity of the screw and its application does not allow to reach the SFS value anymore. This problem can be explained by the necessity to use a prestress between the soft material and the wood. The normal stresses needed to activate the friction create high stresses in the wood near the screw and the wood is already plasticized before the beginning of the loading. In that case, even a friction coefficient higher than one (not physical) is not sufficient to resolve the problem. By consequence, a new method of modelling have been developed with cohesive surfaces instead of contact and friction. This one will allow to obtain a set of parameters which is compatible in all the cases.

2.2.2. Smooth 3D elements with a cohesive behaviour

Concept. Models similar to the ones with contact and friction have been developed with cohesive surfaces. A cohesive surface can be considered like a 3D system of strings which are positioned perpendicular to the surface of contact and in the 2 principal directions of the surface. The 2 surfaces in contact (soft material/wood) are glued each other until a shear stress limit is reached and the "glue" allow a small slip thanks to the rigidity parameters. In our case, it has been decided to use springs only in the longitudinal direction of the surface (parallel to the screw axis). By the way, it is possible for the screw and the soft material to rotate when the wood is embedded without the appearance of tension stresses on the opposite side and shear stresses on the lateral sides.

Properties. The main properties of the model are shown in Table 3. The Stress limits of the Hill criterion are the mean values for spruce [11] and the smallest one is chosen between tension and compression properties. The mean values allow a correlation with the experimental tests more easily. Indeed, the characteristic values, especially for tension, are much lower and lead to yielding too rapidly. The properties which are used for the CLT panels and the screws are taken from Table 1 and 2.

Table 3: Main properties of the model with cohesive surfaces.

Hill criterion (mean values [11])			
$F_{c,0,mean} = F_{t,0,mean}$	$45MPa$	$\tau_{12} = \tau_{13}$	$7MPa$
$F_{t,90,mean} = F_{c,90,mean}$	$3MPa$	τ_{23} (rolling shear)	$3.5MPa$
Soft material			
Radial E modulus	$50MPa$	Tang. and long. E mod	$370MPa$
G modulus	$690MPa$	Poisson coefficients	0
Cohesive surface			
Long. rigidity	$40N/mm^3$	Tang. and rad. rigidities	$0N/mm^3$
Shear stress limit	$5MPa$	Damage evolution	linear ($0N$ after $4mm$)

Results. Results shown in Figure 7 represent the modelling study based on the Jockwer's model. The experimental device has been modelled carefully with the properties discussed before. As it can be seen, the gaps between the curves are very small whether for the rigidity, the ultimate load and the post-failure behaviour.
Results shown in Figure 8 represent the triumphal arches. In that case, the ultimate loads are similar for the different screwing angles but the rigidities are not correct. This fact can be explained by small differences between the modelling and the real configuration. The numerical model contains only one screw and the panels are supposed perfectly motionless in the direction perpendicular to the panels plane. In the experimental, the sample is composed of 3 panels which are fixed by 4 screws and the external panels cannot move toward or away thanks to beams which are added (see Figure 2 (left)). So, the lateral rigidity is not infinite (the beams can bend for high forces) and the global rigidity is lower. For this reason, more complex models representing the real geometry have been developed. The results are shown thereafter.

Calibration. Many calibrations have been done to arrive to the parameters shown before. Pull-out tests and triumphal arches have been used for this

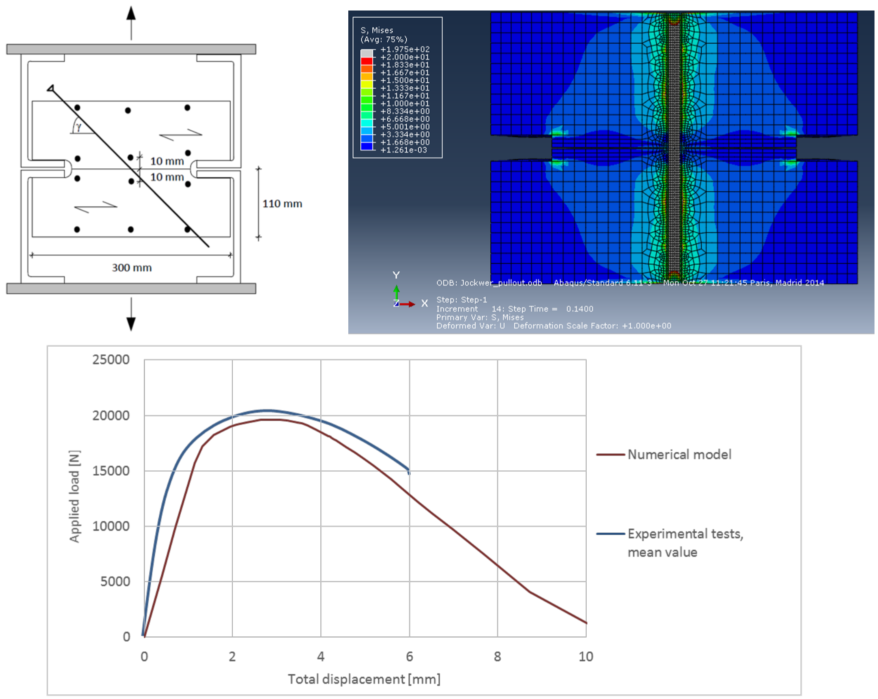

Figure 7: Pull-out modelling based on R. Jockwer experimental tests [9] [10].

purpose. The main part of these calibrations concerned the soft material and two conclusions can be derived of it.
The longitudinal modulus of elasticity of the soft material impacts directly the rigidity of the assemblies in pull-out tests. This parameter has any influence on triumphal arches (loading perpendicular to the screw axis)
The radial modulus of elasticity of the soft material impacts directly the rigidity of the triumphal arches.
By the way, it is possible to calibrate easily the model for the more opposed behaviours (axial and transverse loading) and any model which is between these opposites (screws at different angles) could be valid.

Validation have been done for another type of triumphal arches (8 screws) with screwing angles of 30° in compression and in tension. The results are shown in Figure 9. Considering the variability of the experimental results and the fact that only one test is made for this configuration, the correlation seems promising. Other experimental tests will be made in the near future to validate and calibrate more precisely the numerical models.

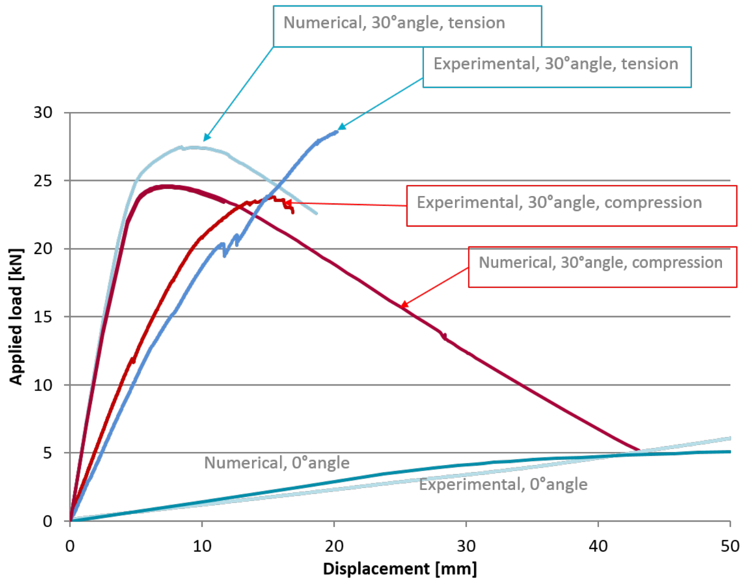

Figure 8: Triumphal arches. Numerical and experimental results for different screwing angles.

3. Discussion and concluding remarks

The scientific mission has fulfilled is main objective, namely get a new method of modelling which is more robust, rapid and precise. The goal was obtained thanks to the use of cohesive surface and the development of a "soft material" which represents an unknown zone of the screwed assemblies, the thread part. The methodology of modelling has allowed to obtain one set of parameter which is correct for all the experimental tests (triumphal arches, different angles, pull-out etc.). Given that the variability of the experimental tests is not know for the moment (few number of experimental tests), it is difficult to calibrate more accurately the results. Nevertheless, the results are promising, with gaps between experimental and numerical which are generally lower than ten percent.

4. Publication

It is planned to further analyse and improve the models as well as the experimental tests. It is also intended that the results will be published in a near future.

5. Acknowledgement

I would like to thank Prof. Erik Serrano for his hospitality and availability as well as for his help at my arrival and the facilities. I also thank the members

of the structural mechanics department of Lund University for their welcome. I thank Dr Thierry Descamps and the civil engineering and structural mechanics department of Mons University for letting me perform this STSM and for the laboratories management during my absence.
Finally, I thank the members of the COST FP1004 action for their support.

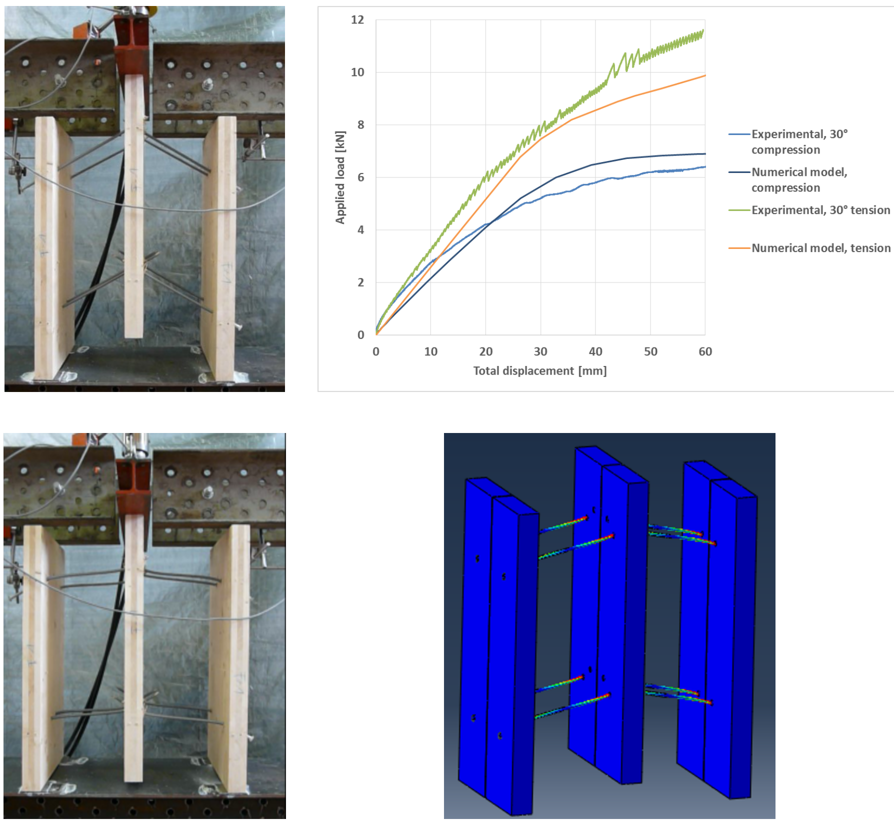

Figure 9: Triumphal arches with screwing angle of 30° in compression and tension.

References

[1] L. Léoskool, T. Descamps, L. Van Parys, V. Rodríguez Trujillo, Cross-laminated timber: Towards a consistent structural insulated panel for passive buildings in belgium, in: proceedings of the 13th World Conference on Timber Engineering (WCTE 2014), 2014.

[2] Österreicheisches Institut für Bautechnik, Eta-06/0138 - solid wood slab element to be used as structural elements in buildings, Tech. rep., European Organisation for Technical Approvals (EOTA) (2011).

[3] Österreicheisches Institut für Bautechnik, Eta-12/0062 - sfs self-tapping screws wr, Tech. rep., European Organisation for Technical Approvals (EOTA) (june 2012).

[4] L. Léoskool, T. Descamps, Development of a structural insulated panel (sip) with wood-based material, in: COST Action FP1004 Conference, Experimental Research in Timber, 2014. `doi:10.13140/2.1.3567.0727`.

[5] L. Léoskool, T. Descamps, J. Noël, G. Puissant, Behaviour of screwed cross-laminated timber panels, numerical and experimental analyses, in: B. Topping, P. Iványi (Eds.), Proceedings of the Twelfth International Conference on Computational Structures Technology (CST 2014), Civil-Comp Press, 2014. `doi:10.4203/ccp.106.256`.

[6] R. Hill, A theory of the yielding and plastic flow of anisotropic metals, in: Oxford (Ed.), Proceedings of theRoyal Society of London. Series A, Vol. 193, Mathematical and Physical Sciences, 1948.

[7] T. Descamps, D. Lalisse, S. Datoussaïd, 3d fem modeling of slender laterally loaded timber fasteners, in: C. Associates (Ed.), Proceedings of the 12th International Conference on Fracture, 2009.

[8] T. Descamps, L. Van Parys, S. Datoussaïd, Development of a specific finite element for timber joint modeling, in: International Journal for Computational Methods in Engineering Science and Mechanic, Vol. 12, 2011, pp. 1–13.

[9] R. Jockwer, R. Steiger, A. Frangi, Fully threaded self-tapping screws subjected to combined axial and lateral loading with different load to grain angles, in: S. Aicher, H.-W. Reinhardt, H. Garrecht (Eds.), Materials and Joints in Timber Structures, Vol. 9 of RILEM Bookseries, Springer Netherlands, 2014, pp. 265–272. `doi:10.1007/978-94-007-7811-5_25`.

[10] R. Jockwer, Structural behaviour of glued laminated timber beams with unreinforced and reninforced notches, Ph.D. thesis, ETH Zurich (2014).

[11] Trækonstruktioner: Beregning, SBI-anvisning, Statens Byggeforskningsinstitut, SBI, 1994.