Design tool for adhesive free timber structures

L. Bouhala, D. Fiorelli, A. Makradi, S. Belouettar

Luxembourg Institute of Science and Technology,
5, rue Bommel, ZAE Robert Steichen L-4940 Hautcharage, G.D. Luxembourg

Abstract

A numerical tool is developed to design adhesive free timber structures made of doweled laminated wood elements. These novel engineered wood products are made of timber plates assambled by densified wood dowels. The numerical tool is based on mechanical model describing the specific behaviour of wood: plasticity induced damage under compression and brittle failure under tensile loading. The model is calibrated using compression, tensile and bending tests on densified and no-densified raw material and validated subsequently by considering tests on doweled structures. A generic Python script for each test was developed and used repeatedly for parametric studies. All the numerical aspects are controlled by a user-friendly graphical interface where relevant results are displayed and simultaneously compared with the experimental ones.

1. Introduction

Nowadays, Engineered Wood Products (EWPs) market knows a great expansion because of new climate change policies and legislations (Kyoto Protocol, Cancún Agreement, Durban Platform). Structures made of engineered wood such as glued laminated timber (Glulam) or Cross Laminated Timber (CLT) have significantly increased as structural building material due to their high strength and stiffness to weight ratio. Timber structures are considered as heterogeneous and complex material to model, their structural behaviour leads to numerical non-linearities. Mainly, wooden materials are ductile under compression loading and brittle under tensile and shear loadings. Moreover, their behaviour is anisotropic, i.e. depends strongly on the local material orientation. However, due to the unique cell structure of wood, three planes of material symmetry exist, which makes wood an orthotropic material. [1, 2]. Modelling timber structures is mostly based on specific approaches for different problem classes. Gharib et al. [3] developed an orthotropic 3D constitutive model for fibrous materials and utilized it for the non-linear analysis of timber members where different modes of failure and their representative failure criteria are obtained. Continuous Damage Mechanics (CDM) theory was used to model the stiffness degradation in various stress components and to evaluate the non-linear response under a multi-directional stress state. Zerpa et al. [4] developed a method to identify the elastoplastic parameters of timber. The proposed method enables the user to identify the parameters using data coming from bending or compression experimental tests performed on Uruguayan Pinus taeda timber. Within the present study, numerical simulations based on a robust constitutive law are carried out to model the wood behaviour under severe loading conditions. Thus, the rheological model describing the behaviour of wood material is implemented using finite element method and multi-yield surface plasticity. Therefore, a damage model that counts for tensile-shear brittle failure and compressive ductile damage is introduced.

1. Structural Design Tool

The size, number and arrangement of dowels in adhesive-free compressed-wood dowelled-laminated beams and panels have a significant influence on their structural performance. Analysis of such components is complex generally involving a numerical modelling approach, which can replicate the complex geometry and account for the highly anisotropic behaviour of the timber material. To this end, a design tool is developed presenting a user-friendly interface permitting the user to easily specify the lay-up and dowel arrangement for laminated beams and dowelled laminated panels (Fig. 1). The tool will then generate the complex model input file for the finite element package ABAQUS which may be run to produce numerical results. The geometry generated can also be exported for use in other software packages. This easy-to-use tool can be used to quickly modify the geometry, examine the numerical results and enable the optimisation of the design. The proposed methodology enables the user to design wood structures with different degrees of geometry complexity and without substantial knowledge of an FEA software (e.g. Abaqus). Thus, standardized tests such as the four-point bending tests on laminated timber beams can be studied easily. The methodology needs to build an Abaqus model written as a generic python script where relevant parameters are highlighted and considered as variables. These parameters are introduced via the graphical user interface. The procedure is more interesting for repeated simulations with different geometries or optimization procedures.

Figure 1: design tool features

Because Python is the standard programming language of Abaqus, we developed a GUI in Python environment that comprises different input frames and buttons and offers multiple options. The developed software package, called Structural Design Tool (SDT), see Figure 3, includes the graphical user interface (GUI), the user subroutine (Umat) and several parametrized Abaqus scripts. The validation of the constitutive law, the tuning of its parameters as well the design of timber structures and the settings of standardized tests are done through this intuitive GUI. The user input data are sent from the GUI to an ad-hoc Python script file that contains commands and instructions reproducing all the steps to generate, run and analyse the finite element simulation. This script is readable by Abaqus and able to create parts automatically, apply materials properties, assign sections, define sets and surfaces, define interactions, assembly the parts, apply the boundary conditions and constraints, mesh the structure, run the job and process simulation results. The main results are sent back to the GUI where stress-strain, load-deflection or load-slip curves can be displayed and compared with experimental curves.

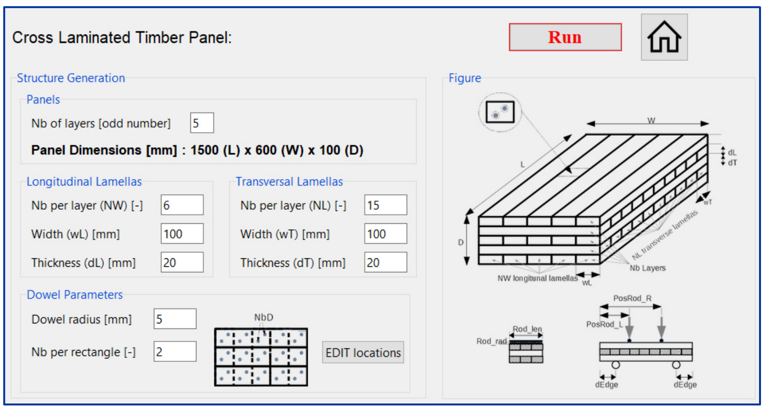

Figure 2 - User Interface of the Structural Design Tool used to design a cross laminated timber panel.

2. Wood constitutive law

Natural wood presents different mechanical behaviour and damage mechanisms under compressive and tensile loadings. Due to the morphological growth of wood, the micro-structure is considered as orthotropic with three major axes: L: along the fibre; R: along the radial direction; and T: along the tangential direction. When subjected to mechanical loadings, the material response includes a combination of all the deformation modes. The strain-based damage models rely on the concept of effective stress and the hypotheses of strain equivalent. Effective stress is defined as the stress acting in the reduced undamaged net surface area of the undamaged material. While, the hypotheses of strain equivalent states that the strain associated with Cauchy stress in the damaged state is equivalent to the strain associated with the effective stress in the undamaged state. Therefore, the Cauchy stress (σ) is expressed function of the effective stress (σ) by:

$\sigma = (1 - w)\ \sigma$, where w is a damage variable. Natural wood shows a brittle failure under tension and shear, and ductile damage under compression. Therefore, to consider this behaviour, the effective stress tensor (σ) is split into tensile component (σ^{+}) and compressive component (σ^{-}) as: $\sigma = \sigma^{-} + \sigma^{+}$

Considering the effective stress splitting, the Cauchy stress can be reformulated in terms of the tensile w^{+} and compressive w^{-} damage variables as: $\sigma = (1 - w^{-})\ \sigma^{-} + (1 - w^{+})\ \sigma^{+}$

It should be noted that in the following study only elasto-plasticity is considered in the constitutive model for the sake of simplicity.

3. Numerical investigation

In this section, we detail three simulation examples generated, launched and the obtained results are processed and displayed using an in-house developed graphical user interface (GUI). The GUI gives the user the choice to design beams/slabs by stacking planks and to assemble them using wood dowels. For structural design without any analysis, Abaqus scripts are short and comprises only sections for geometry generation and assembly. For full analysis, Abaqus scripts are long and contain in addition: Material section (where properties are introduced using a User Material Subroutine), Step section to define the type of the analysis, interaction section dedicated to describe the contact between parts, a section to introduce the loading and boundary conditions, a separate section reserved to mesh parts using different types and sizes of elements, a job section to execute the model where the link to the Umat is defined. Finally, a last important section dedicated to post-process where the results are displayed and analysed.

3.1. Compression and Tensile tests

A three-dimensional cube ($40 \times 40 \times 40\ mm^3$) is considered to undergo uni-axial mechanical compression/tensile loading. Using the GUI, one can run compression/tensile tests for perpendicular to grain or parallel to grain configurations. We found for the same type of wood; the longitudinal direction shows very high properties compared to the other two directions. A good agreement between the numerical results and the experimental one was found. More importantly, the GUI is used in an inverse sense to identify the wood properties. Indeed, the method assumes a set of governing parameters in the constitutive law for each direction and run the simulation in that direction. Combining the numerical and the experimental results in a least square sense by minimizing the error leads to the material properties.

3.2. Push out double shear test

Two series of compressive tests were carried out on joints which comprised of timber sections and compressed wood dowels. We consider here only the first series that involved the compressed wood dowels being inserted so that their radial direction was perpendicular to the longitudinal direction of the timber sections. Scots Pine (Pinus Sylvestris) was used as the timber section and was supplied by Buckland Timber, Devon, UK. The timber was visually graded, and kiln dried to moisture contents of 10 − 15%. The average density of the timber sections was 550 kg/m^3. The compressed wood dowels were also made from Scots Pine (Pinus Sylvestris) with an average density of 1200kg/m^3. The average moisture content of the compressed wood dowels was 5%. One compressed wood dowel was used to fasten the three timber sections together. The aim of the tests was to determine the maximum load and load-slip responses of the joints and was carried out in accordance with the norm BS EN 26891. Therefore, the compressed wood dowels were in double shear. The tests were carried out at a crosshead displacement rate of 2 mm/min using a universal testing machine (Instron 3369) which had a maximum load capacity of 50 kN.

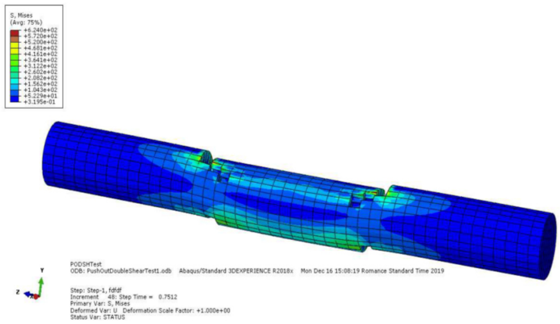

Figure 3: Damaged dowel under double shear load

3.3. Four-point bending test

An adhesive free laminated timber beam (AFLT) was assembled with timber laminates and compressed wood dowels. The AFLT beam was left for seven days (under ambient laboratory conditions) before it was tested to ensure a tight fit between the compressed wood dowels and the timber laminae as a result of the moisture dependent swelling of the compressed wood dowels. Four-point bending tests were carried out on the AFLT beams in accordance with the norm BS EN 408 (2010). The beams were simply supported on steel rollers, and a laser displacement sensor was used to measure the vertical deflection of the beams under loading. The obtained numerical results are compared with the experimental ones, see Figure 2.

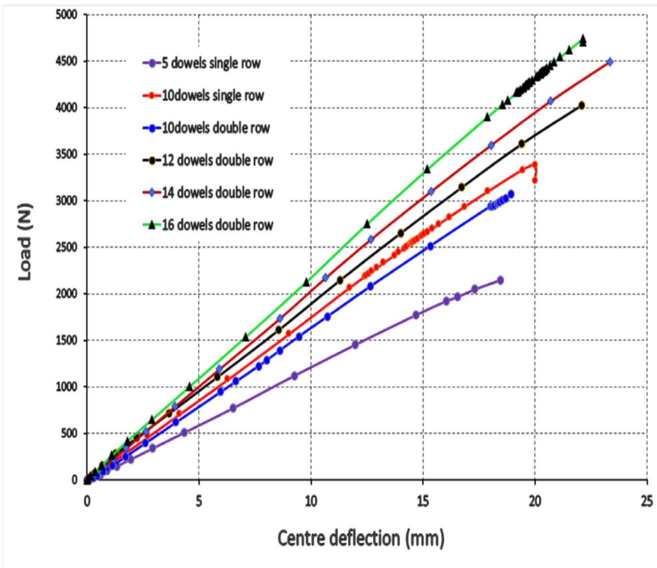

Figure 2: Simulation result of four-point bending test; load vs centre deflection for different number of dowels.

4. Conclusion

A friendly graphical user interface capable of designing complex wood structures and running finite element analysis for several mechanical simulations is developed. It is made possible using generic python scripts developed as Abaqus models. Experimental tests were carried out to validate the constitutive law of wood which is implemented as user-subroutine in the FEA software. The considered structures are adhesive free since they are assembled with only compressed wood dowels. For instance, simple wooden samples were used for tensile and compression tests in the three principal directions. The obtained results are then used in an inverse problem sense to extract the parameters defining the wood properties. Moreover, the calibrated constitutive law is used to simulate the push out double shear test where the results were found in good agreement with the experimental results. This convergence between the numerical and experimental results is represented by the slip-load of the numerical and experimental curves. More importantly, the simulations showed the source of the softening in these curves, which comes from damage onset on the dowels. Furthermore, to check the robustness of the methodology, simulation of the four-point bending test was run for several dowel configurations. Eventually, the developed graphical interface gives big flexibility to handle several structural geometries and dowel configurations. Thus, the investigation can be applied to other parametric studies and numerical tests.

References

[1] Z. Guan, E. Zhu, Finite element modelling of anisotropic elasto-plastic timber composite beams with openings, Engineering Structure 31 (2009) 394 – 403.

[2] P. Mackenzie-Helnwein, J. Eberhardsteiner, H. A. Mang, A multi-surface plasticity model for clear wood and its application to the finite element analysis of structural details, Computational Mechanics, 31 (2003) 204 – 218.

[3] M. Gharib, A. Hassanieh, H. Valipour, M. Bradford, Three-dimensional constitutive modelling of arbitrarily orientated timber based on continuum damage mechanics, Finite Elements in Analysis and Design, 135 (2017) 79 – 90.

[4] J. P. Zerpa, P. Castrillo, V. Baño, Development of a method for the identification of elastoplastic properties of timber and its application to the mechanical characterisation of Pinus taeda, Construction and Building Materials 139 (2017) 308 – 319.