CSCE Annual Conference

Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)

June 12 - 15, 2019

FINITE-ELEMENT MODELLING OF DUCTILE WOOD CONNECTIONS

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Abstract: Typical connections in wood structures consist of structural members connected with thin-walled steel elements, commonly angle brackets. The design of these steel elements is typically based on short-term load bearing capacity experimental testing. Experiences from the experimental testing indicate that both steel plate and connectors possess properties such that these connections can be designed to behave in ductile manner. Following the capacity design principle, during seismic loading the structural members remain undamaged while the damage and most of the energy dissipation is confined within the steel elements. However, there is insufficient support in Building Design Codes to design any building for a seismic situation in such a manner. This paper presents development of numerical models of the connections and subsequent validation by experimental results. Their applications in replicating performance of a number of metal bracketed connections with these characteristics are illustrated. Two sources of ductility for the overall arrangement, namely deformations in the metal connectors and in screws (bending and pulling out) due to cyclic loading have been identified. The steel plate absorbs significantly less energy after the first circle while the screws can dissipate energy more consistently over the cycles, characterized by pinching and elasto-plastic behavior respectively. The models offer insights into detailing ductile connections in wood and possibility in the optimization of the connectors for seismic design.

1 INTRODUCTION

Typical connection details are well-established and in use in traditional wooded structures for a long time. With increasing number of applications where wood is primary structural material there is demand to develop new types and details to meet high level of performance objectives with modern structures. That is particularly true for wooded structures designed for seismic regions. Connections intended for this type of applications are investigated here with numerical models.

2 DUCTILE CONNECTIONS FOR WOODEN MEMBERS

In order to dissipate energy during seismic shaking connection details of a structure need to have the allowance and capacity to deform throughout the event. It is therefore essential for connections to be designed for ductility. One convenient way of achieving ductility is to confine most of deformation within the metal connection elements while protecting the wooden structural members. Due to the deformation capacities of metals connectors can accommodate significant distortions without complete failure. They are often attached to the members with metal nails or screws which act as additional ductile elements.

There have been studies on this type of connections and their performances (Otani 1980, Stewart 1987, Riedar 2009). In addition, numerical models of their hysteretic behavior have been developed in general (Bouc 1967, Wen 1976) and for material-specific connections such as concrete (Otani 1981) and wood (Dorwick 1986, Foliente 1995, Kivell et al. 1981).

3 NUMERICAL MODELLING OF CONNECTIONS

A finite-element model in Abaqus® (Dassault Systèmes Simulia Corp, 2018) was assembled to simulate the global behaviour of connections under the external loading. The numerical modelling approach followed the previously presented work (Schweigler et al. 2018, Izzi et al. 2018). At the first stage, the simulation was focused on a monotonic loading test with the goal to extend the model to be used for the cyclic loading in future. A parametric modelling approach using Python script is used allowing to change easily material properties and geometry of angle brackets, wooden beams and connectors for the application in various metal works.

3.1 Modelling approach

Wood material model is defined by nine engineering constants (E_l=9700 MPa, E_r= 220 MPa, E_t= 220 MPa, v_{lr}=0.0, v_{lt}=0.0, v_{rt}=0.0, G_{lr}=400 MPa, G_{lt}=25 MPa, G_{rt}=25 MPa) representing longitudinal "l", radial "r" and tangential "t" directions of the modulus of elasticity "E", Poison's coefficient "v" and shear elastic modulus "G". The longitudinal direction corresponds to the length vector for each beam in the test setup. Timber beams are partly modelled by 2-node linear beam elements in space and partly by 8-node linear brick elements. Volume (brick) elements are used in close surrounding of angle brackets whereas beam elements are used to simulate the rest of the wood material in the experimental setup.

Steel material model of angle brackets is defined by combination of elastic and plastic constants E_{S250} = 210 GPa, v_{S250}=0.30, f_y = 250 MPa, f_u = 420 MPa (at plastic strain 40%). An 8-node doubly curved general-purpose shell elements are used to simulate the angle brackets in the connection. Contact between the shell of angle brackets and adjacent surface of timber beams is defined as frictionless hard contact allowing separation after the contact.

Material model of screws is defined by elastic constants E_{screw} = 630 GPa and v_{screw}=0.30. A 3-node quadratic beam in space elements are used to simulate each screw in the tested connection. The interaction between the edges of holes in the angle brackets and screws is solved by kinematic constraints connecting edges of holes to reference points placed in the center of each hole. The reference points in the centers of holes are connected to the screws by connector elements allowing to simulate both nonlinear elastic spring behaviour in translation and plasticity. The interaction between the screws and timber is solved by ten connector elements equally distributed on each shank of each screw. These connectors are connecting nodes of timber volume (brick) elements and beam elements of screws and are defined as combination of plastic and nonlinear elastic behaviour in translation.

3.2 Simulation of single screw in timber volume

To calibrate the properties of each individual connector connecting the shank of screw to the timber volume and edge of hole in the angle bracket, simulation of single lap steel plate to timber volume connection by one screw was used. The model presented in Figure 1 simulates the effect of loading of the head of the screw by rotation of angle bracket. It also simulates the response of a single screw to biaxial displacement. The visualisation of the numerical simulation results shows von Mises stress over the screw shank and in the steel plate. The sketch of the numerical model defines by colours symbols of connectors used in the model. The colors of the lines in the force to displacement diagram correspond to the colors of the connector in the sketch. In this particular case presented in Figure 1, the force to displacement diagram indicates rigid behaviour in lateral direction and nonlinear elastic behaviour in the screw longitudinal direction. The application of this connector behaviour allows to simulate the pinching effect of the screw during the withdrawal cyclic test.

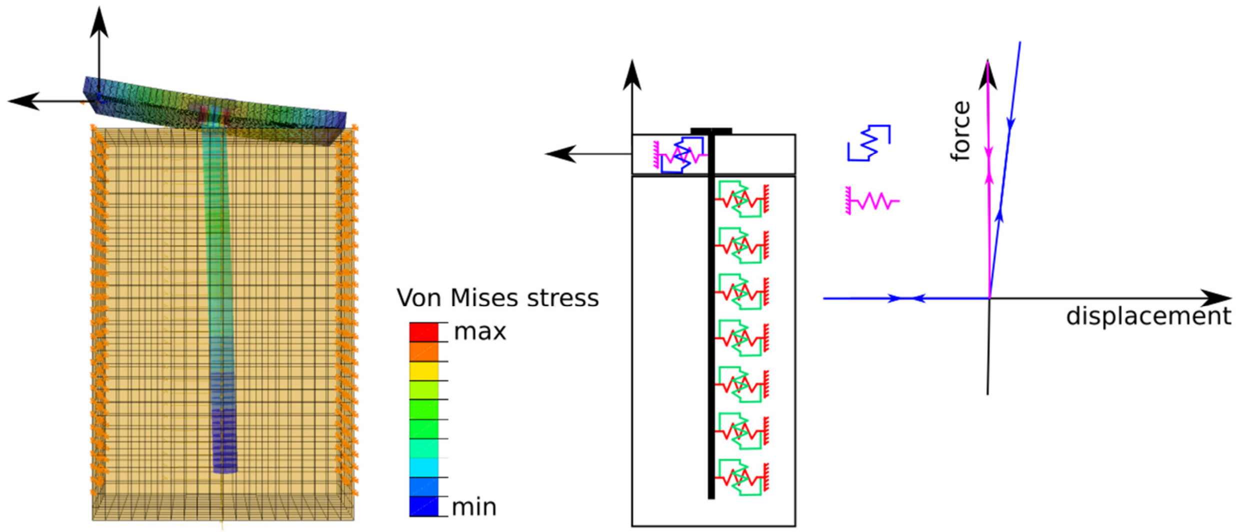

Figure 1: Illustration of simulation of single lap steel plate to timber volume connection by one screw.

The model presented in Figure 2 simulates simple withdrawal test of screw from the timber volume in the axial direction of screw. The visualisation of the numerical simulation results shows von Mises stress over the screw shank. The sketch defines by colours symbols of connectors used in the model. The force to displacement diagram describes the response of each nonlinear spring connector used to connect the screw to the timber mesh in the screw longitudinal direction. The axial withdrawal simulation is used to compare force-to-displacement diagrams from the industrial monotonic and cyclic tests to the simulation results.

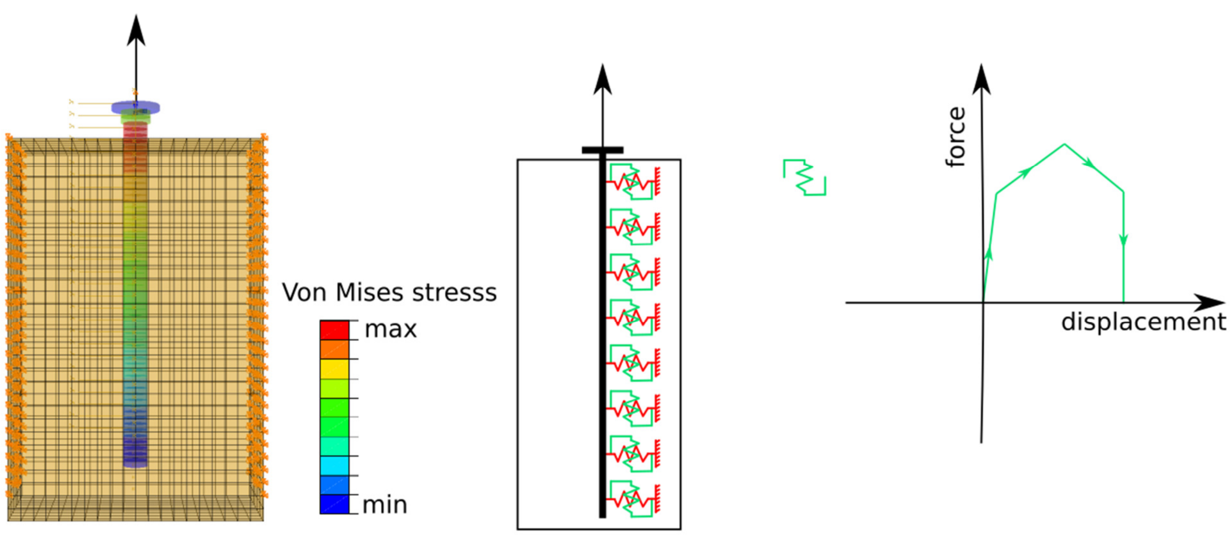

Figure 2: Illustration of simulation of single screw withdrawal test.

The model presented in Figure *3* simulates shear test of screw in the lateral direction of screw. The visualisation of the numerical simulation results shows von Mises stress over the screw shank. The sketch defines by colours symbols of connectors used in the model. The force to displacement diagram describes the response of each nonlinear spring connector used to connect the screw to the timber mesh in the screw lateral direction. Lateral shear simulation is also used to compare force-to-displacement diagrams from the industrial monotonic and cyclic tests to simulation results. The influence of the timber grain direction to the simulation results is neglected since the wood material model has unified properties in radial and tangential direction.

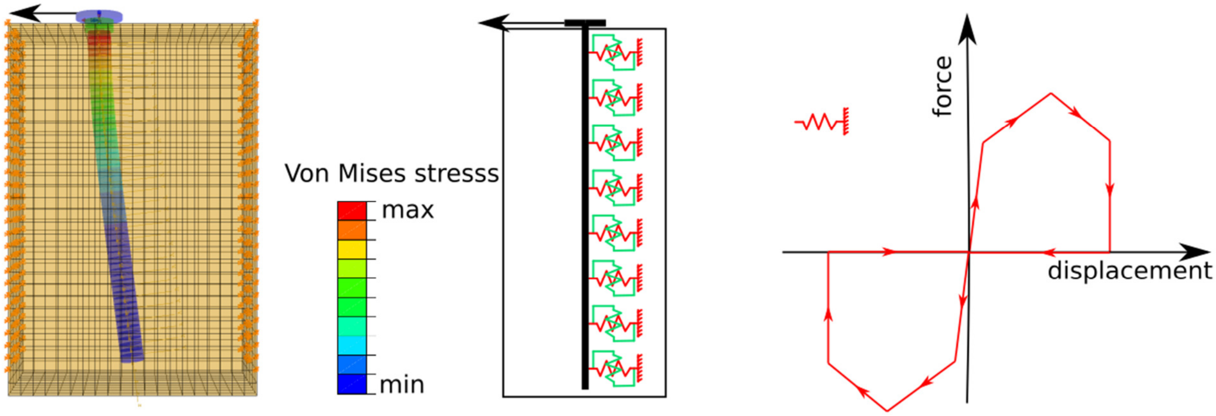

Figure 3: Illustration of four applications of single screw model in timber volume.

The connector definition derived from simulation presented in Figure *2* was used in the simulation presented in Figure 3. The connector definition from simulations presented in Figures *2* and 3 was used in the simulation presented in Figure 1.

3.3 Whole connection numerical model

The calibrated single screw model was applied to the whole connection model. To avoid mesh sensitivity of the model, timber surrounding each screw is partitioned similarly to the model of single screw in timber volume. In Figure 4, the simulation of experimentally tested connection of timber blocks by angle bracket ABR9020 (Simpson 2016) is presented.

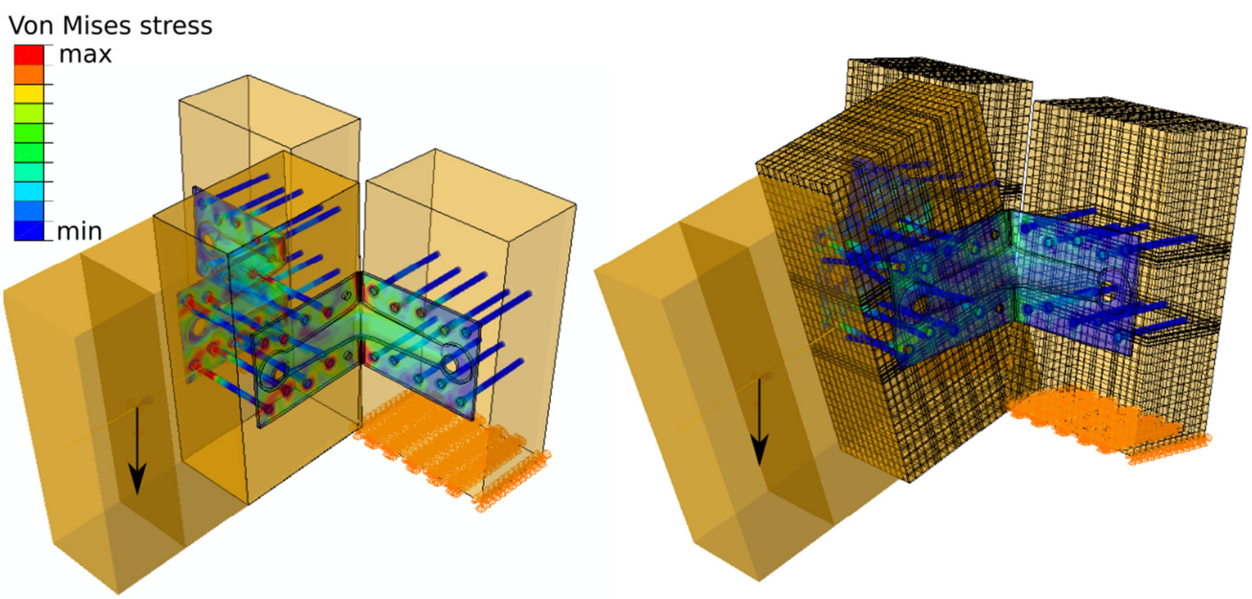

Figure 4: Stresses and magnified deformed shape in numerical simulation of tested connection.

Symbols at the bottom side of two smaller blocks represent boundary conditions fixing three degrees of freedom in translation of every node of the block (density of symbols is not defined by mesh but by partitions). These two smaller blocks represent timber parts modelled by volume (brick) elements. The bigger block represents the timber part which is partly modelled by volume elements and partly by beam elements. In Figure 4, the volume elements have highlighted edges, whereas beam elements have highlighted centrelines. The boundary conditions causing displacement of bigger timber block are marked by arrow acting in the centreline of beam element. In the model, there is allowed translation in the direction of the centreline of the timber block. Colour field in Figure 5 represents the magnitude of von Mises stress in the connection model and redistribution of load to individual screws in the connection. The deformed shape of the whole connection is also shown in Figure 5.

4 CONCLUSIONS

Numerical models of connections designed for ductility are investigated in the current research. Behavior of elements both individually and collectively are studied with single screw and whole connection models. Although the numerical simulation of the connection is at its early stage and is not compared to the experimental data yet, it shows valuable benefits of the approach. The screw modeling approach by beam elements with nodes directly attached to the nodes in the volume of timber is relatively lightweight compared to the modelling approach using volume elements for modelling of connectors. On the other hand, using multiple connectors over the shank of the screw allows to simulate the damage of wood material close to the surface of the timber beams affecting both, the axial an lateral resistance of the appropriate part of the shank whereas the properties of connectors placed deep in the timber volume may rest unaffected. Compared to the point-based modelling approach of whole screws, the used model seems to be more applicable for cyclic behaviour simulation which is going to be used in future.

Acknowledgements

The research was partially funded by Forestry Innovations Investment of British Columbia, Canada under the Wood first program. Details of the brackets were provided by the manufacturer Simpson Strong-Tie of Maple Ridge, BC, Canada. All the supports are gratefully acknowledged.

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