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BEAM-ON-ELASTIC FOUNDATION MODEL OF MECHANICAL PROPERTIES OF RING NAILS AND HEAVY-DUTY SCREWS

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ABSTRACT: Beam-on-foundation modelling shows huge potential to substitute the limit analysis and empirical stiffness formulas used to calculate the load bearing capacity of timber connections with dowel-type fasteners like nails and screws. It takes into the account the non-linear behaviour of fastener's shank subjected to bending as well as the elastic-plastic behaviour of contact between the fastener and surrounding wood. Its another advantage is the capability to calculate both capacity and stiffness of complex connections commonly used in cross-laminated timber structures. This paper describes numerical models of axially and laterally loaded fasteners in wood. Results from modelling are thereafter compared to the experimentally obtained data.

KEYWORDS: Timber connections, heavy-duty screws, threaded nails, numerical simulation, Python scripting.

1 INTRODUCTION

During the late twentieth century, the limit analysis proposed by Johansen [1] replaced the empirical formulas used to determine the load bearing capacity of dowel-type timber connections. However, Johansen's simple design equations are becoming insufficient to cope with present-day challenges, which are e.g. related to the design of high-rise wooden buildings [2]. Former developments in computational mechanics made it possible to develop both simple [3,4] and advanced [5-9] numerical methods which take into the account the nonlinear phenomena. These approaches have remained unused in practical design due to their complex implementation and their high running time, at the time of their invention, while nowadays computational resources would allow fast and efficient numerical methods-based design. The aim of this paper is to test the applicability of these numerical methods to calculate the capacity and stiffness of various fasteners like ring nails and screws in steel-to-CLT connections.

2 EXPERIMENTAL TESTING

Mechanical properties of four types of fasteners (listed in Table 1) in CLT panels were the scope of the experimental testing.

Table 1: *Overview of used fasteners in connections.*

Fastener	Length	Shank diameter
CNA4-60	60 mm	4.0 mm
SDS10212	63.5 mm (2.5 in)	4.1 mm
SDS25112	38.1 mm (1.5 in)	4.7 mm
SDS25300	76.2 mm (3.0 in)	4.7 mm

For each fastener, two types of test-setups were assembled: to test fastener in the axial direction for withdrawal (Figure 1) and to test fastener in the lateral direction for shear (Figure 2). During each test, load magnitude applied to the fastener's head was recorded. Displacement from its original position was measured only at the fastener's head and its magnitude was related to the adjacent surface of the CLT panel. In addition, observed failure modes were noted down for each tested specimen.

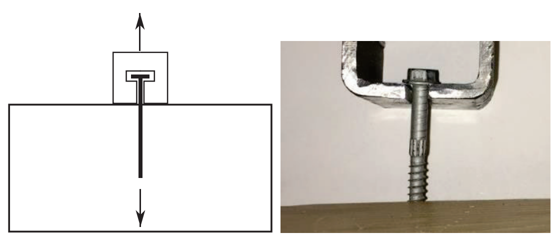

Figure 1: *Illustration of the experimental setup of axially loaded fasteners: schematic (left) and during tests (right).*

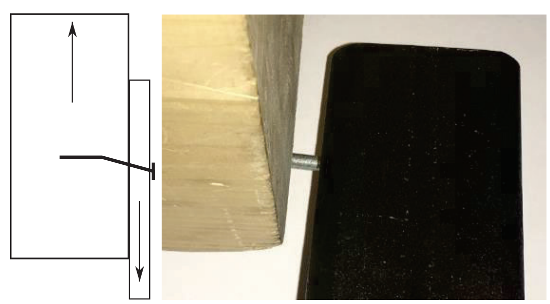

Figure 2: *Illustration of the experimental setups of laterally loaded fastener: schematic (left) and during tests (right).*

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The aim of the experimental testing was to find the stiffness and load bearing capacity in order to compare it to the results from the simultaneously made numerical simulations.

3 NUMERICAL SIMULATIONS

The numerical models assembled in the Abaqus® software consist of beam elements representing fasteners, surrounding timber volume serving as a foundation and a number of nonlinear spring elements connecting nodes of beam elements to nodes of the surrounding volume made of timber. These nonlinear springs act both, in the axial and in the lateral direction of the fastener. Both the axial and the lateral properties are discretized according to the experimentally based data from the fastener withdrawal and shear tests. A similar approach has been previously successfully used by Izzi in [8] and Gikonyo in [10].

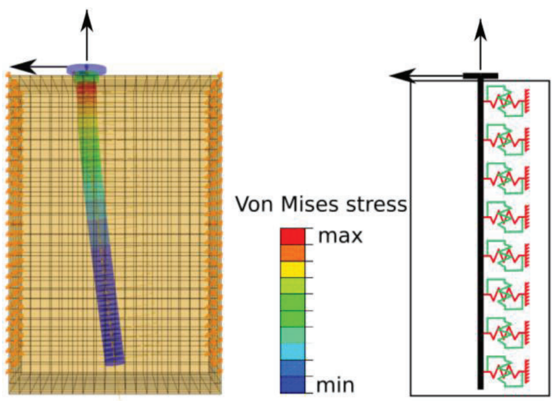

Figure 3: *Illustration of numerical model of single fastener used to simulate both test (lateral shear and axial withdrawal).*

The model presented in Figure 3 shows the single fastener after the simulation of the shear test (in the lateral direction of the fastener). The visualisation of the numerical simulation results shows von Mises stress over the shank of the fastener. The symbolic sketch outlines the way how the nonlinear spring connectors connect timber mesh to the shank of the fastener. The use of the sufficient number of spring element prevents the overloading of nodes of the mesh. 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.

4 RESULTS AND DISCUSSION

The presented meshes obtained by the numerical models in Abaqus (figures 4 a nd 5) illustrate that 2 mm distance between the nonlinear springs placed at the shank of the fastener is a good compromise between the detailed model and reasonable computational cost.

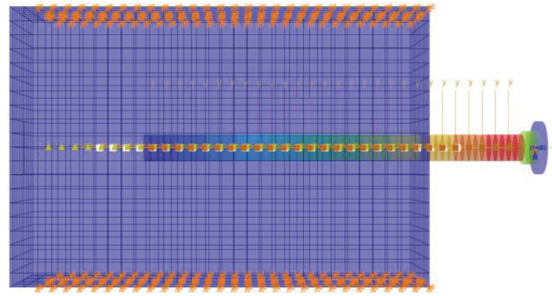

Figure 4: *Von Mises stress from numerical simulation of withdrawal of the CNA 4.0x60 nail from CLT.*

Since the withdrawal stiffness of the nonlinear springs used in the model is just the division of the overall axial stiffness of the fastener, the maximum of von Mises stress occurs at the location of the first spring (see Figure 4). This might be changed in order to get the result of the simulation closer to the real behaviour when the pulled-out fastener loses the contact with the surrounding timber.

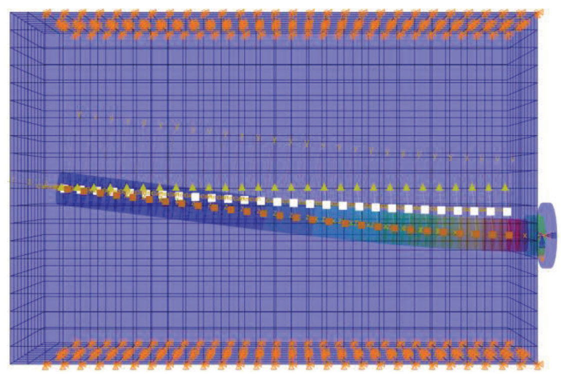

Figure 5: *Von Mises stress from numerical simulation of lateral shear slip of the CNA 4.0x60 nail in CLT.*

The stiffness of the nonlinear spring acting in the lateral direction of the shank of the fastener represents the embedment stiffness of the CLT material. The transfer of load between the fastener and the timber material is simplified by assigning the steel material properties to the parts of the mesh in the close vicinity (not exceeding the diameter of the fastener) of the beam representing the shank of the fastener. The important parameter influencing the behaviour of the model is the bending stiffness of the nail shank.
The following presented load-displacement curves for the individual fasteners in CLT bring a direct comparison between the experimentally and numerically obtained results as well as between the nails and screws.

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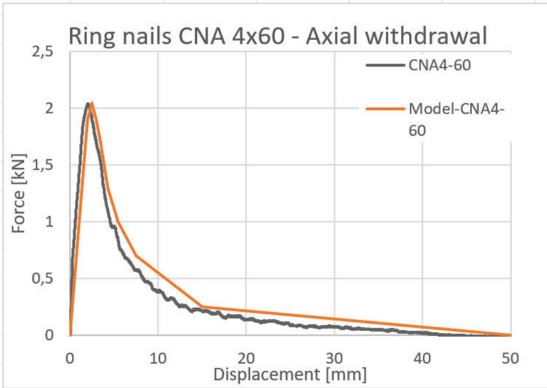

Figure 6: *Results of numerical simulation of CNA 4.0x60 NAIL in CLT connection compared to the numerical simulation.*

One representative specimen from the tested annular ring nails was chosen to be compared to the mechanical parameters used in the model (see Figure 6). It is the one which is closest to the mean behaviour of the tested sample. The spring model of the nail uses the elastic stiffness equal to 2333 N/mm. The rest of the curve is defined by nonlinear plasticity.

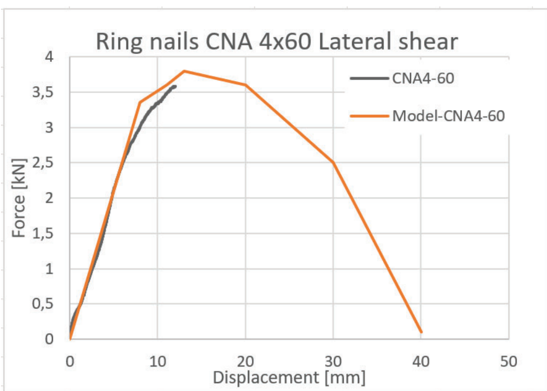

Figure 7: *Results of numerical simulation of CNA 4.0x60 NAIL in CLT connection compared to the numerical simulation.*

One representative specimen from the tested annular ring nails was chosen to be compared to the mechanical parameters used in the model (Figure 7). It is the one which is closest to the mean behaviour of the tested sample. The spring model of the nail uses the elastic stiffness equal to 1014 N/mm. The rest of the curve is defined by nonlinear plasticity. The part of the curve which was not found by the test was extrapolated by using the knowledge of the behaviour of similar nails in a similar material.

Figure 8: *Results of numerical simulation of SD10212 screw in CLT connection compared to the numerical simulation.*

One representative specimen from the tested screws was chosen to be compared to the mechanical parameters used in the model (see Figure 8). It is the one which is closest to the mean behaviour of the tested sample. The spring model of the nail uses the elastic stiffness equal to 2750 N/mm. The rest of the curve is defined by nonlinear plasticity.

Figure 9: *Results of numerical simulation of SD10212 screw in CLT connection compared to the numerical simulation.*

One representative specimen from the tested screws was chosen to be compared to the mechanical parameters used in the model (see Figure 9). It is the one which is closest to the mean behaviour of the tested sample. The spring model of the nail uses the elastic stiffness equal to 1000 N/mm. The rest of the curve is defined by nonlinear plasticity. The part of the curve which was not found by the test was extrapolated by using the knowledge of the behaviour of similar nails in a similar material.

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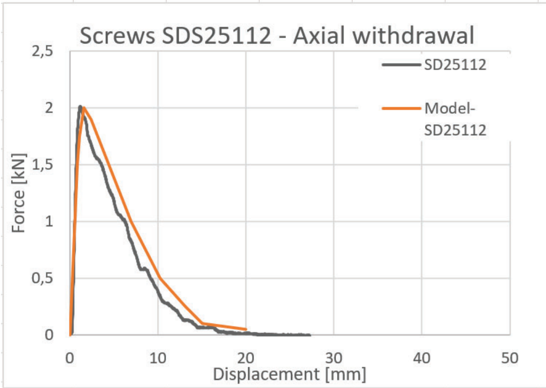

Figure 10: *Results of numerical simulation of SDS25112 screw in CLT connection compared to the numerical simulation.*

One representative specimen from the tested screws was chosen to be compared to the mechanical parameters used in the model (see Figure 10). It is the one which is closest to the mean behaviour of the tested sample. The spring model of the nail uses the elastic stiffness equal to 2000 N/mm. The rest of the curve is defined by nonlinear plasticity.

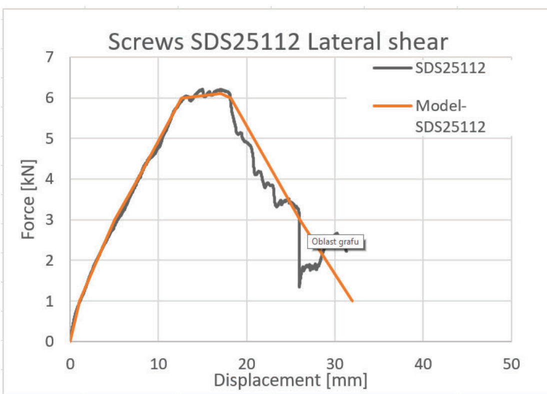

Figure 11: *Results of numerical simulation of SDS25112 screw in CLT connection compared to the numerical simulation.*

One representative specimen from the tested screws was chosen to be compared to the mechanical parameters used in the model (see Figure 11). It is the one which is closest to the mean behaviour of the tested sample. The spring model of the nail uses the elastic stiffness equal to 2000 N/mm. The rest of the curve is defined by nonlinear plasticity.

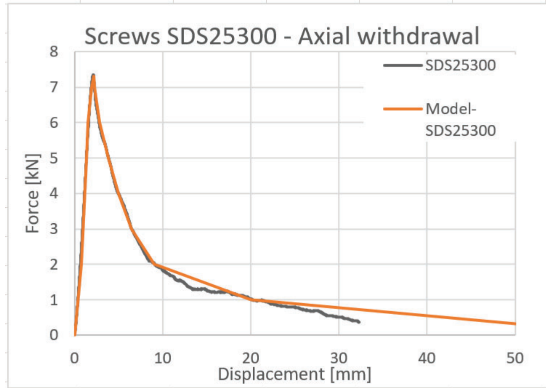

Figure 12: *Results of numerical simulation of SDS25300 screw in CLT connection compared to the numerical simulation.*

One representative specimen from the tested screws was chosen to be compared to the mechanical parameters used in the model (see Figure 12). It is the one which is closest to the mean behaviour of the tested sample. The spring model of the nail uses the elastic stiffness equal to 8000 N/mm. The rest of the curve is defined by nonlinear plasticity.

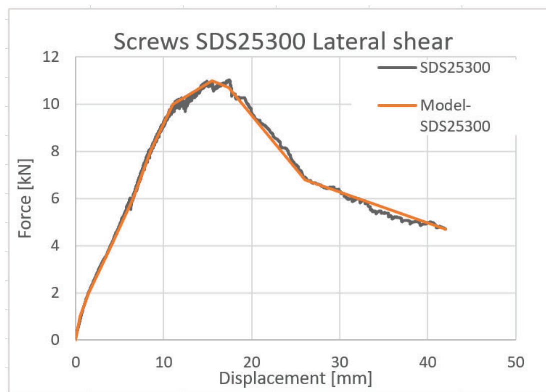

Figure 13: *Results of numerical simulation of SDS25300 screw in CLT connection compared to the numerical simulation.*

One representative specimen from the tested screws was chosen to be compared to the mechanical parameters used in the model (see Figure 13). It is the one which is closest to the mean behaviour of the tested sample. The spring model of the nail uses the elastic stiffness equal to 2000 N/mm. The rest of the curve is defined by nonlinear plasticity.
In addition, the overall comparison of tested fasteners is presented in following two figures.

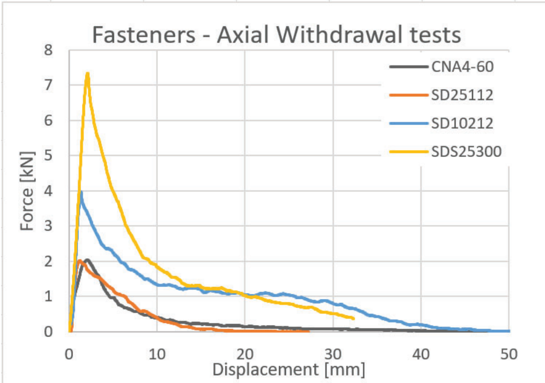

Figure 14: *Representative mechanical behaviour of three types of screws and one type of nail subjected to the withdrawal test.*

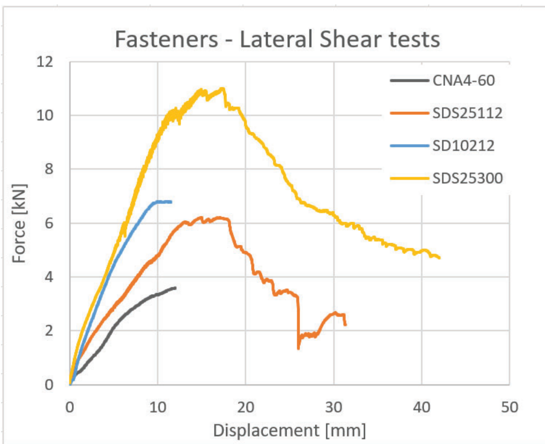

Figure 15: *Representative mechanical behaviour of three types of screws and one type of nail subjected to lateral shear test.*

5 CONCLUSIONS

The modelling approach by beam elements whose nodes are attached to the nodes in the volume of timber by nonlinear springs is relatively lightweight compared to the modelling approach using volume elements and friction for modelling fasteners in wood material. On the other hand, the approach with springs distributed over the shank of the fasteners has an advantage to the single-spring modelling approach of whole fasteners, because using the appropriate number of nonlinear springs allow to allocate the damage of the timber material to the top part of the fastener's shank whereas the properties of connectors placed deep in the timber volume may rest unaffected. Another advantage is a better simulation of coupling since the springs which are close to surface can resist to the shear and the rest of the springs can resist to the withdrawal.

Using multiple connectors over the shank of the screw also allows to simulate relatively easily a complex phenomenon of the cyclic mechanical loading of the fasteners. In this case, damage of wood material close to the surface of the CLT panels occurs, which affects both the axial and lateral resistance.

Another useful application of the proposed model of the presented fasteners can be the case when the connection is subjected to the combination of the axial and lateral loading (as shown in Figure 16). This has not been tested yet. Therefore, it is a scope of the further research to subject the screws and nails to this type of loading and compare the experimental results to the data obtained by numerical simulations.

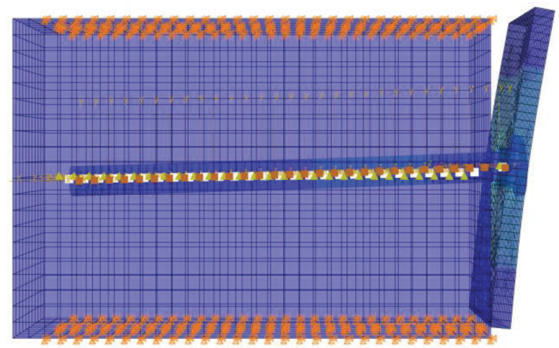

Figure 16: *Von Mises stress from numerical simulation of CNA 4.0x60 nail in CLT subjected to the combination of lateral (shear) and axial (withdrawal) load.*

The combination of the axial and lateral loading is a typical for connections of CLT elements by angle brackets (see Figure 17). It is a topic of an ongoing research to apply the fastener model in a simulation of mechanical loading of a more complex connection and compare the experimental results to the data obtained by numerical simulations (see Figure 18).

Figure 17: *Experimental setup of CLT connection made of angle bracket ABR9020 and screws.*

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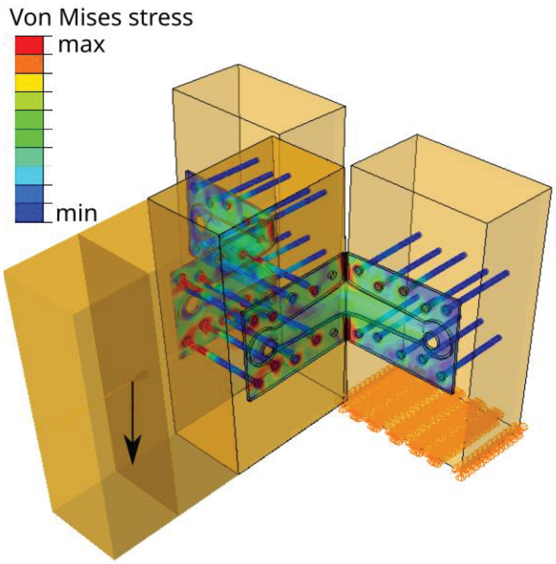

Figure 18: *Von Mises stress from numerical simulation of loaded CLT connection with ABR9020 angle brackets with CNA 4.0x60 nails in CLT.*

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