Numerical modelling of connection of timber beams using angle brackets with a rib

Petr Sejkot[1,2,4], **Sigurdur Ormarsson**[3],

[1]Department of Steel and Timer Structures, CTU in Prague, Thákurova 7, 166 29 Praha 6, CZ
[2]UCEEB of CTU in Prague, Třinecká 1024, 273 43 Buštěhrad, Czech Republic (CZ)
[3]Linnaeus University, Växjö, Sweden

E-mail: petr.sejkot@uceeb.cz

Short Term Scientific Mission by Petr Sejkot, of Czech Technical University in Prague, Czech Rep. to Linnaeus University, Växjö, Sweden, between 11th April and 10th May 2015.

1. Purpose of the Short Term Scientific Mission

Timber connections using thin-walled metal elements gradually supplant traditional carpentry joints. Their main advantage is that they do not significantly weaken the connected timber elements. Other advantages include the possibility of in-situ implementing or the possibility of direct connections of timber elements to steel and concrete structures. Important advantage is also their ductile behavior when subjected for load [1].

Their main disadvantage is the very complex behavior when subjected for load. Connections using angle brackets are often loaded from various directions. The load distribution to the nails is not uniform and is not easily predictable because of high ductility of the metal plates. Moreover, deformed metal plates also cause prying of nails which is loading them by an additional bending moment. That's why any standardized calculation procedure to determine their load bearing capacities is missing and connections using metal works are mostly designed according to the producer's experimentally based catalogues.

This situation is not very convenient for a designer to address, because they have only very limited possibilities of checking these values by using simplified analytical calculation models.

Developing new and reliable calculation models of connections using metal works is desired both by producers and by designers. Producers will profit from it by faster and cheaper development of their products. On the other hand, designers will be able to check their designs in a more precise way.

One of the most convenient ways of analyzing connections using metal works is to use the finite element method in 3D space.

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[4] To whom any correspondence should be addressed.

2. Description of Research

The test set up used to determine the load bearing capacities of beam to beam connections made by nailed angle brackets with a rib has been simulated with a 3D-model in Abaqus CAE. It aims to compare the numerical results with the experimental behavior.

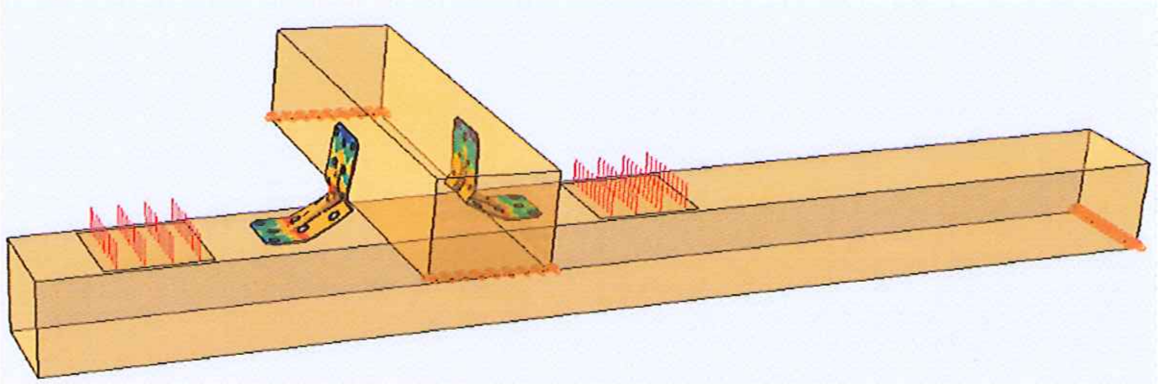

Fig. 1 Geometry of the test set up used in FEM model

Boundary conditions in the simulation were according to the real test set up. That is pinned end of longer shoulder of lower beam and both ends of upper beam (see Fig. 1).

In the experiment, the connection was loaded by using load distribution device symmetrically transferring the external loading force to two areas on the lower beam of the connection (marked by red vertical lines indicating trajectory of its motion).

Angle brackets are modelled as shell elements with attached thickness. The steel material used is considered as an elastic-plastic material with a yield stress σ_y= 280 MPa.

Timber beams are modelled as solid members. The wood material is assumed to be an orthotropic material with the elastic parameters E_l=9700 MPa, E_r=400 MPa, E_t=220 MPa, ν_{lr}=0.35, ν_{lt}=0.60, ν_{rt}=0.55, G_{lr}=400 MPa, G_{lt}=250 MPa, G_{rt}=25 MPa used in [2].

Nails were modelled as connector elements with properties based on the experimental data of annular ring nails connecting holes edges of angle brackets to rigid bodies in timber beams. Axial behavior of the connectors was based on data provided by Czech nail producer Hašpl a.s. Lateral behavior was based on data provided by Linnaeus University in Växjo, Sweden.

Although the provided data were not from nails with the exactly same length and diameter as nails used in the connection, only the following observed essential behavior characteristics were adopted to the connection simulation: For the axial direction, the measured characteristic load bearing capacity of axially loaded nails was 75% of its mean load-bearing capacity, while its motion was only 67% of the motion in failure (see Fig. 2). For the lateral direction, the characteristic load bearing capacity of laterally loaded nails was 83% of its mean load-bearing capacity, while the motion was only 50% of the motion in failure (see Fig. 3).

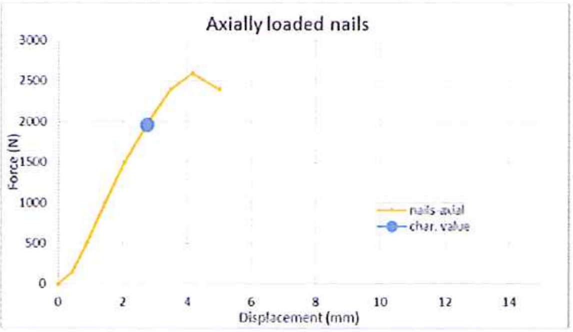

Fig. 2 Force-displacement diagram of axially loaded threaded nails (d=4.0 mm, l = 90 mm)

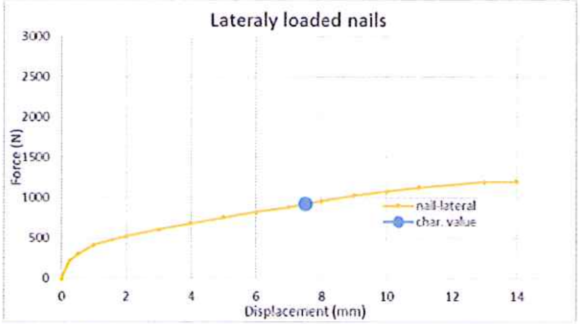

Fig. 3 Force displacement diagram of laterally loaded threaded nails (d=2.5 mm, l=40 mm)

According to the observed characteristics, three sets of simplified force-displacement diagrams of nail behaviour were created to be used in simulation. The first set was from rigidly-ideally plastic diagrams with yield forces equal to calculated characteristic load bearing axial and lateral capacities of used nails according to EC5 [3] and DIN 1052:2004 [4] (see Fig. 4). The second set was created with respect to the ratios of mean to characteristic capacities of tested nails, hence rigidly-ideally plastic diagram of nails behaviour in both axial and lateral direction were made (see Fig. 5). And the third set was made by adopting displacements of both, axially and laterally loaded nails caused by characteristic and maximal forces, so that two rigidly-linear force displacement diagrams were made (see Fig. 6).

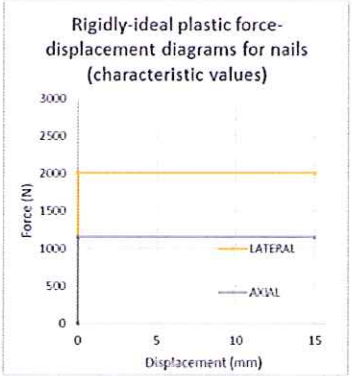

Fig. 4: Characteristic capacities used for rigidly-ideal plastic force-displacement diagrams for nails in axial and lateral direction.

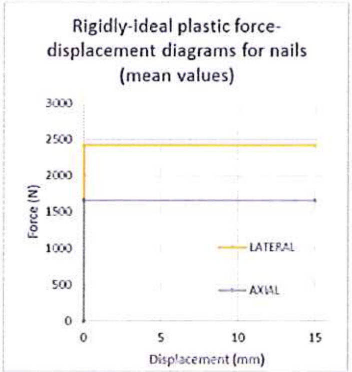

Fig. 5: Mean capacities used for rigidly-ideal plastic force-displacement diagrams for nails in axial and lateral direction.

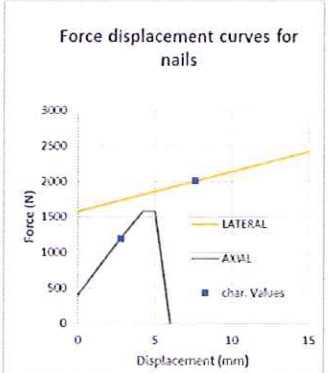

Fig. 6: Rigidly-linear plastic force-displacement diagrams for nails based on diagrams of threaded nails in axial and lateral direction.

The nail behavior from Fig. 4 was implemented to numerical model and simulated force-displacement behavior was compared to the characteristic load bearing capacity of the tested connections using angle brackets (see Fig. 1). The same approach was used to compare mean load bearing capacity with using mean behavior of nails presented in Fig. 5. And finally, the behavior of tested connections was compared to behavior of numerical models of connection using nail behavior presented in Fig. 6.

The used way when every nail is represented by a rigid body in the timber beam connected to the appropriate hole edge in the angle bracket by connector with predefined behavior can simulate following behaviors in the connection: Groups of rigid bodies simulate the behavior of the timber blocks affected by groups of nails connecting the planes of angle brackets to beams. Each linear connector simulates both, lateral and axial behavior of every single nail in the connection. And by using damage condition, lateral load reduces the maximum axial load which can be applied to the loaded nail.

Despite these simplifications, the behaviour of whole simulated connection with applied external load quite well conform the behaviour of connections during the load test (see Fig. 7).

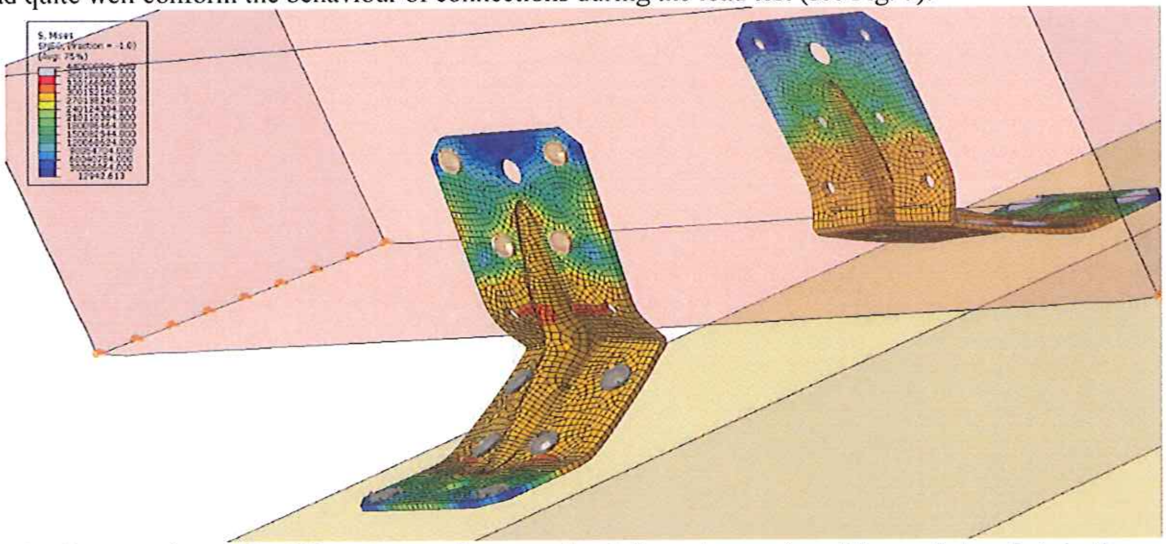

Fig. 7: Contour plot of Von Mises stresses shown on the deformed geometry of the angle brackets in the connection.

Moreover, the benefit of simplification of these simulation models is that it is easy to create them and it can be adopted not only by researches but also by practical engineers. Since, these models have been experimentally verified they can be used to calculate load carrying capacity for other load configurations

2.1. Experiments

Before the start of the STSM, full scale experiments of beam to beam connection (upper beam 100x100x400 mm, lower beam 100x100x1110 mm, see Fig. 1) made by two different versions of angle bracket with a rib were performed at CTU in Prague. Ten specimens of the first angle bracket version were tested before the start of the research. Then the results were analyzed and geometry improvements suggested. Finally, five specimens of the improved version of angle brackets was produced (by BOVA Březnice s.r.o.) were experimentally tested and their behavior was analyzed.

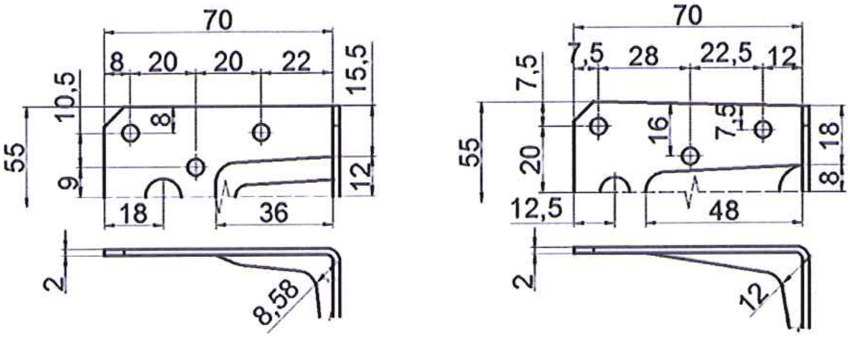

Fig. 8: Angle brackets dimensions in millimetres (left – original version, right – improved version)

Both types of angle brackets were made of hot-dip galvanized steel sheet, 2 millimeters thick, classified as S280GD+Z275 (see Fig. 8).

Both sets were loaded according to the similar load diagrams based on expected load-bearing capacities of tested angle brackets (i.e. 8.50 kN for original one and 10.0 kN for improved one). In the first 120 seconds of the test, the connection was loaded to the 40% of its expected load bearing capacity and rested there for 30 seconds. Then, in 90 seconds the load was reduced to 10% of expected load-bearing capacity and rested there for 30 seconds. And finally, it was loaded till the collapse by 3.33% of expected load-bearing capacity per second.

Partial load bearing capacities were determined by two limits – collapse and maximal displacement of 15 mm. The force was applied by a hydraulic cylinder with a preset loading program in time. Displacement was sensed by a group of sensors. All input data were synchronized in the measuring center.

2.2. Evaluation procedure

The evaluation procedure combined four methods of the assessment of tested specimens.

The density was evaluated according to Eurocode 0 [5] with added reductions respecting the timber joints specifics described in EOTA TR 16 [6] and ISO 8970 [7].

The final load-bearing capacity was evaluated according to the EN 14358 [8] with added reduction from EOTA TR 16 [6] taking into account the difference between the measured and standardized densities.

3. Results and discussion

The experimentally determined load-bearing capacities of the connections were compared to the results from numerical simulations.

Although, the connection is made by two angle brackets and displacement distribution in the same direction as the external loading force can be considered as being uniform, there are significant differences in the force distribution to each angle bracket. This fact was not neglected in the results evaluation.

3.1. Experimentally determined load bearing capacities

The measured densities of tested angle brackets are compared in Table 1 .

Table 1. Evaluation of measured densities

	Specimens	Mean density *(kg/m^3)*	Standard deviation *(kg/m^3)*	Characteristic density *(kg/m^3)*
05-21 - original	10	447.9	32.1	386.3
05-21 - improved	5	424.2	23.6	369.1

Compared to table densities in EN 338 [9] of timber strength class C24 ($\rho_{mean} = 420$ kg/m^3, $\rho_k = 350$ kg/m^3), it is obvious that the used timber has a significantly better quality than is required for the appropriate strength class.

Table 2. Consideration of the natural variation of wood density with respect to measured load-carrying capacities

	COV_ρ *(%)*	COV_δ *(%)*	EN ISO 8970	COV_R *(%)*	k_{cov}
05-21 – original	7.16	12.41	Not satisfied	15.99	1.2881
05-21 - improved	5.57	13.01	Not satisfied	16.46	1.2652

In both sets, there were samples which did not fulfil density conditions from EN ISO 8970 [7] . This fact resulted in a high value of the factor k_{cov} (see Table 2).

Table 3. Evaluation of measured load-bearing capacities

	Mean value transformed to timber strength class C24 (*kN*)	Characteristic value (*kN*)
05-21 – original	12.324	8.50
05-21 - improved	17.492	11.67

Table 3 shows load-bearing capacities of both types of angle brackets. Load bearing capacity of each connection was determined either by collapse of the connection or by 15 mm displacement.

It is noticeable that the improvement of the shape and nail positions of the angle bracket brought an over 30% improvement in the load bearing capacity.

From every set of experiments, two important curves were pointed out. The mean load compared to mean displacement and characteristic forces measured per every millimeter of displacement (see Fig. 9).

It is important to point out measured densities in every test set (see Table 1).

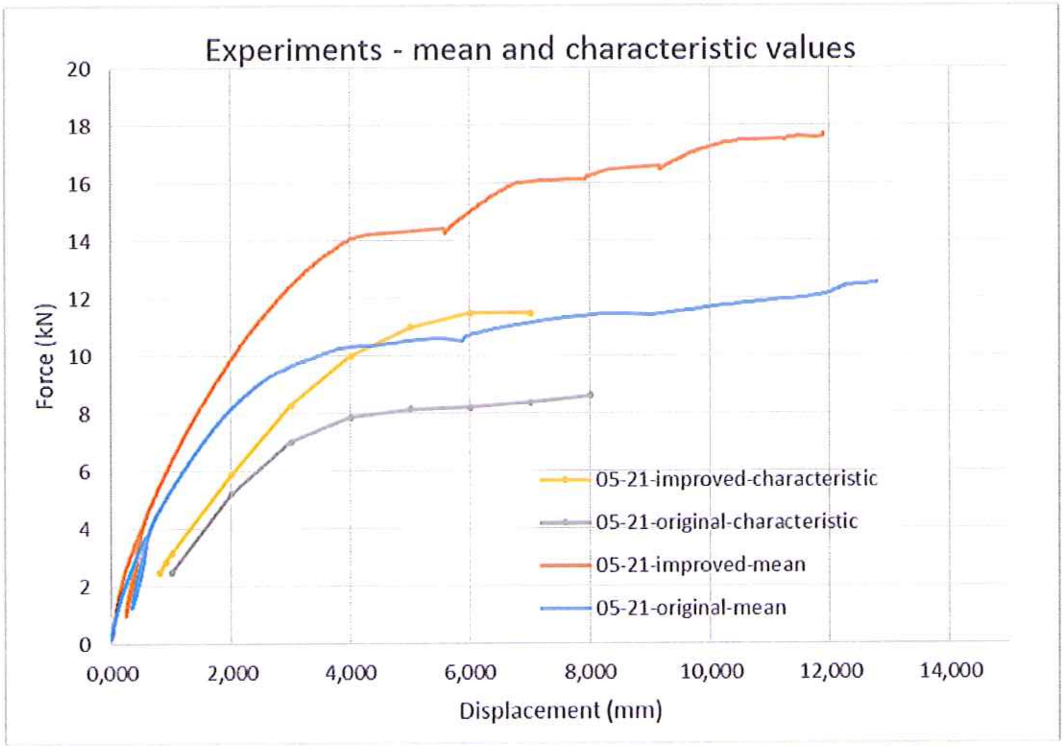

Fig. 9: Mean forces per displacement compared to characteristic forces per displacement

3.2. Numerically determined load-bearing capacities

Numerical models of the whole beam to beam connection brought complete force to displacement diagrams. These diagrams were compared to the experimentally determined force to displacement diagrams.

Figures below (Fig. 10 and Fig. 11) show results with simplified nail behavior to rigidly plastic. The plastic behavior starts at the values determined by calculation according to the EC5 and DIN 1052:2004. In the Fig. 10 nail's "yield force" is assumed to be their characteristic load bearing capacity (in both axial and lateral direction) and the behavior is compared to characteristic load-bearing capacities from full-scale experiment. In the Fig. 11 nail's "yield force" is assumed to be their mean load bearing capacity (in both axial and lateral direction) and the behavior is compared to mean load-bearing capacities from full-scale experiment.

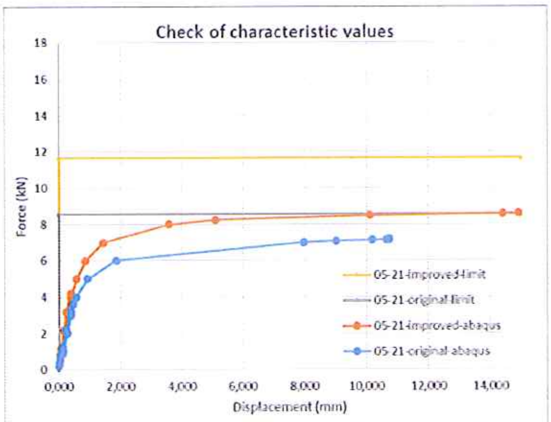

Fig. 10 Experimentally determined characteristic load-bearing capacities compared to results from model using characteristic rigidly-plastic nail models (Fig. 4)

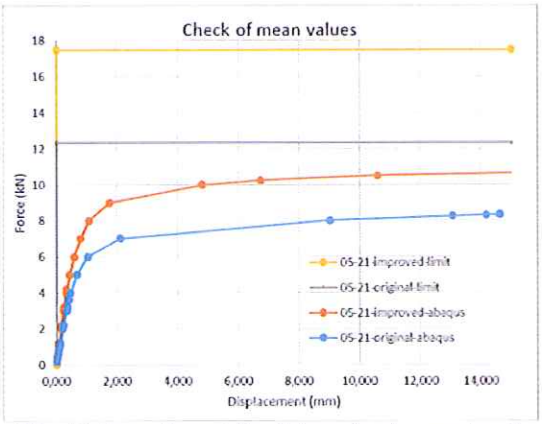

Fig. 11 Experimentally determined mean load-bearing capacities compared to results from model using mean rigidly-plastic nail models (Fig. 5)

As it is evident from the plots, rigidly plastic model is better in predicting characteristic load-bearing capacities than in predicting mean load-bearing capacities.

Figures below compare results obtained by simulation with rigidly linearly plastic nail behaviour. In Fig. 12 it is compared mean behavior of the experimentally studied connection to the simulated behavior of the connection using nail load-bearing capacities adequate to nails in timber class C24. In Fig. 13 nails load-bearing capacities are calculated with using mean densities of timber used in each connection set.

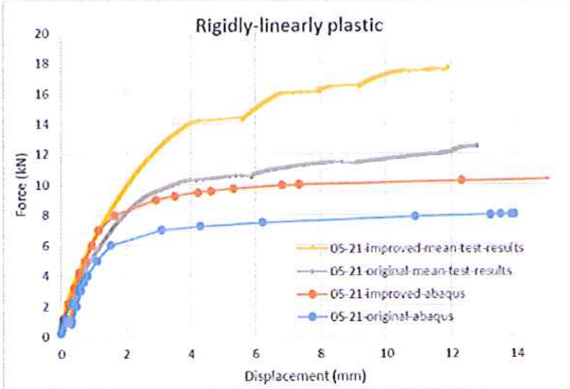

Fig. 12 Mean force-displacement curves of opening of the gap between the connected beams under the applied external load. The model data used for nails are based on density of timber class C24.

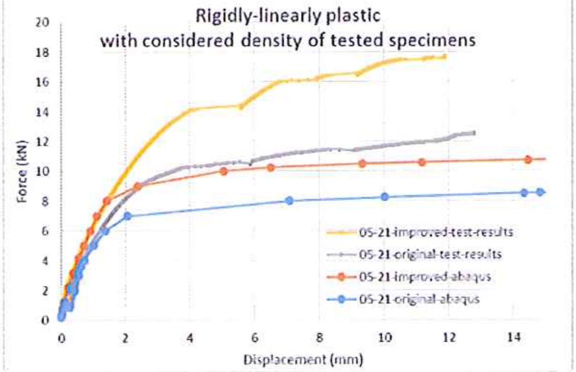

Fig. 13 Mean force-displacement curves of opening of the gap between the connected beams under the applied external load. The model data used nails are based on mean density of timber measured in tests.

As it is evident from the plots, increased load bearing capacity of nails by considering measured densities of timber in tested elements has very low effect to the simulated behaviour of connections.

All the simulations match quite well with the real behaviour until it start to behave nonlinearly. This quite high difference between mean load bearing capacities of tested connections compared to the results from numerical simulations can be explained by neglecting of the prying of nails. It happens because angle bracket deformation induce a bending moment to nails fixed in its holes. This bending moment increases the pressure of threaded part of the nail on the timber and increases its withdrawal resistance.

This behaviour is different to the lateral load, which mainly increases stress at the not threaded part of the nail. This do not increase its withdrawal resistance, conversely it reduces it because of the rope effect and the plastic motion.

To determine the the influence of prying of the nails, a parametric study was made. Fig. 14 shows results where characteristic and mean load-bearing capacities of nails are multiplied by two compared to the model from Fig. 13. This indicates that this effect is very important in these connections.

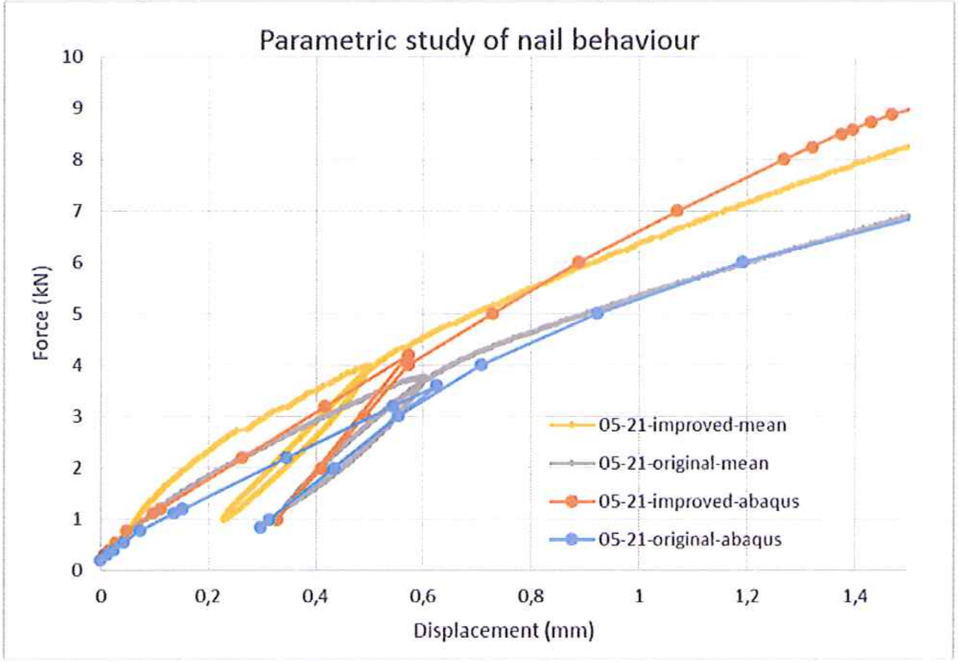

Fig. 14: Parametric study of prying of nails

4. Conclusions and future collaboration

This project has represented a sharing of resources and knowledge between the Czech Technical University in Prague and Linnaeus University in Växjö for the purpose of understanding how to determine load bearing capacities of spatial connections using metal works by numerical modelling in Abaqus CAE. In the numerical simulations simplified material and nail models were used and results were compared to the experimentally studied behavior. Although the experiments are not dramatically expensive or time consuming, numerical modelling proved to be cheaper, faster and reasonably reliable.

In future, collaboration between the institutions will continue on the further analysis and presentation of results in the topic. There are also opportunities for further analysis of these connections and the expertise gained by researches from both institutions are going to be used to in practice.

Publication

It is intended to publish these results to disseminate the details of the method successfully used in this mission and to form basis for future study. The first ongoing publication is at 2nd International Conference "Innovative Materials, Structures and Technologies (Organized by the Faculty of Civil Engineering, Riga, Latvia, 30.09. - 02.10.2015) where the results from this STSM will be presented during the oral presentation and also in conference proceedings published in SCOPUS database.

Acknowledgments

The authors would like to acknowledge the contribution of the staff in the Department of Building Technology at Linnaeus University, Växjö and the Faculty of Civil Engineering at Czech Technical University in Prague and the financial support of Cost Action FP1004 through Short-term Scientific Mission grant.

Confirmation by the host institution (by Prof. Sigurdur Ormarsson)

Mr. Petr Sejkot has during his one month stay at Linnaeus University, from April 11th to May 10th, been able to perform the work set out in the planning of STSM. The work performed has contributed to an interesting conference paper. Mr. Sejkot is going to present the paper in Riga at the 2nd International Conference of Innovative Materials, Structures and Technologies, Sept 30 – Oct 02, 2015. The paper will also be presented in an open access proceedings published in the SCOPUS database. It has been great pleasure to collaborate with Petr. He is working on very important topic and he is very interested in modelling. I look very forward for further collaboration with Petr and his colleagues at CTU in Prague.

On behalf of the host institution: Sigurdur Ormarsson
Sigurdur Ormarsson, Professor

References

[1] Šťastný R., *Tenkostěnné ocelové tvarované elementy používané v dřevařském inženýrství, ,* 2005, doctoral thesis CTU in Prague, Faculty of Civil Engineering.

[2] Ormarsson S., Dahlblom O., Petersson H., *Numerical Study of Shape stability of Sawn Timber Subjected to Moisture Variations, Part 2: Simulation of Drying Board,* 1998a, to appear in Wood Sci and Technol. 33: 407-423

[3] EN 1995-1-1 Eurocode 5: *Design of Timber structures – Part 1-1: General – Common rules and rules for buildings.* CEN 2006.

[4] DIN 1052:2004: *Design of Timber Structures – General rules and rules for Buildings.* 2004-088

[5] EN 1990 Eurocode 0: *Basis of structural design. Ed. 2*

[6] EOTA TR16: *Method of testing Three-Dimensional Nailing Plates with examples.* TECHNICAL REPORT 16, EUROPEAN ORGANISATION FOR TECHNICAL APPROVALS, 2012.

[7] EN ISO 8970: *Timber structures – Testing of joints made with mechanical fasteners – Requirmentsfor wood density.* CEN 2010.

[8] EN 14358: *Timber structures – Calculation of characteristic 5-percentile values and acceptance criteria for a sample.* CEN 2007.

[9] EN 338: *Structural timber – Strength clases.*, CEN 2003