Determination of Load Bearing Capacity for Spatial Joint with Steel Angle Brackets

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Abstract. The design of spatial connections in load bearing timber structures with steel angle brackets has insufficient support in the existing design standards. Therefore, research has been necessary to improve this state of the art. In the current paper an experimental study on two designs of angle brackets is presented and the results from full-scale experiments are compared to numerical and analytical computational models.

1. Introduction
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 implementation or the possibility of direct connection of timber elements to steel and concrete structures. Their ductile behavior when subjected to load is another important advantage [1].

A steel angle bracket that is normally fastened to timber using annular ring nails (see figure 1) is the most common thin-walled metal connector.

Their main disadvantage is a very complex behavior when subjected to 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, i.e. loading them by an additional bending moment. So far any standardized calculation procedure to determine their load bearing capacities is missing and connections using metal works are mostly designed according to the producers’ experimentally based catalogues.

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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 designers. Producers will profit due to 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.

2. Numerical simulations
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 [2] (see figure 2). It aims to compare the numerical results with the experimental behavior presented in this paper.

Boundary conditions in the simulation were set according to the real test set-up, that is, the pinned end of the longer shoulder of the lower beam and both ends of the upper beam (see figure 2).

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 in figure 2).
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 $\sigma_y = 280$ 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, $\nu_{lr}=0.35$, $\nu_{lt}=0.60$, $\nu_{rt}=0.55$, $G_{lr}=400$ MPa, $G_{rt}=250$ MPa, $G_{lt}=25$ MPa used in [3].

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

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

According to the observed characteristics, simplified force-displacement diagrams of nail behaviour were created to be used in numerical simulations for both axial and lateral behaviour of nails. Characteristic load-bearing capacities of the nails used were calculated according to EC5 [4] and DIN 1052:2004 [5]. Mean values were created with respect to the ratios of mean to characteristic capacities of the tested nails. Displacements were adopted from the force-displacement curves of the tested nails (see figure 4).

![Figure 3. Force-displacement curves for nails (axially loaded: d=4.0 mm, l = 90 mm, laterally loaded: d=2.5 mm, l=40 mm).](image1)

![Figure 4. Idealized force displacement curves for the same nails as were used in full-scale experiments (d=4.0 mm, l=60 mm).](image2)

The nail behavior from figure 4 was implemented to numerical model and simulated force-displacement behavior was compared to the behavior of the tested connections. The way used, 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 the 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 behavior of the whole simulated connection with the applied external load quite well conforms to the behavior of the connections during the load test (see figure 5).

**Figure 5.** 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 they can be adopted not only by researches but also by practicing engineers. Since these models have been experimentally verified, they can be used to calculate load carrying capacity for other load configurations.

3. Experiments

Full scale experiments on beam to beam connection (upper beam 100x100x400 mm, lower beam 100x100x1110 mm, see figure 2) made by two different versions of an angle bracket with a rib were performed. Ten specimens of the first angle bracket version were tested at the beginning of the research. Then the results were analyzed and geometry improvements were suggested. Finally, five specimens of the improved version of angle brackets were produced (by BOVA Březnice s.r.o.), then they were experimentally tested and their behavior was analyzed (see figure 6).

**Figure 6.** Angle bracket dimensions in millimetres (left – the original version, right – the improved version).
Both types of angle brackets were made of hot-dip galvanized steel sheet, 2 millimeters thick, classified as S280GD+Z275.

Both sets were loaded according to the analogical load diagrams based on the expected load-bearing capacities of tested angle brackets (i.e. 8.50 kN for the original one and 10.0 kN for the improved one). In the first 120 seconds of the test, the connection was loaded to the 40% of its expected load bearing capacity and left in that state for 30 seconds. Then, in 90 seconds the connection was uniformly unloaded to 10% of the expected load-bearing capacity and left in that state for 30 seconds. And finally, it was loaded till collapse by 3.33% of the 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 between the connected beams was sensed by a group of sensors. All input data were synchronized in the measuring center.

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

Density was evaluated according to Eurocode 0 [6] with added reductions respecting timber joint
specifics described in EOTA TR 16 [7] and ISO 8970 [8].

The final load-bearing capacity was evaluated according to EN 14358 [9] with the added reduction from EOTA TR 16 [7] taking into account the difference between the measured and standardized densities.

4. Analytical models of the connection
Two analytical models were compared with the experimental results. The first one was an elastic model inspired by research in Trento [10]. The second one was a plastic model, which considered the approach from EOTA TR 17 [11].

Both methods took into consideration the research conclusions from the research conducted by the university in Karlsruhe that annular ring nails of 4 mm in diameter behave in 2 mm thick steel plate in the same way as being in a thick plate [12] and that their axial resistance has squared relation to density [13].

4.1. Elastic model
The elastic model describes the behavior and force distribution before significant deformations occurred (see figure 7).

![Figure 7. Deformed angle bracket during the elastic phase.](image)

Figure 7. Deformed angle bracket during the elastic phase.

![Figure 8. Schema of the elastic model.](image)

Figure 8. Schema of the elastic model.
The load-bearing capacity is determined according to the elastic model, where the resisting features are the corner of the angle bracket pushed to purlin and nails loaded both axially and laterally. In the vertical branch of the angle bracket, lateral load is uniformly distributed to all nails and withdrawal forces are linearly increasing from the corner to the edge of the angle bracket. The forces in the nails are balanced by the pushed corner of the angle bracket to the timber. The bending moment is transferred by a rib to the horizontal branch of the angle bracket. In the horizontal branch, the bending moment is balanced by linearly distributed withdrawal forces acting on the nails there (see figure 8).

4.2. Plastic model
The plastic model describes the behavior and force distribution just before the collapse (see figure 9). The static schema of this plastic analytical model is presented in figure 10.

![Figure 9. Deformed angle bracket during the plastic phase.](image1)

![Figure 10. Schema of the plastic model.](image2)

The calculation is based on “The example of a spatial joint of timber elements by steel angle bracket loaded in a direction that is opening to the angle”. This example was published in the Technical Report 17 (TR 17) [11], which was released by the European Organisation for Technical Approvals (EOTA). The load bearing capacity is determined according to the model, where the resisting features are two plastic hinges and a group of nails in tension. The influence of pushing edge of the angle bracket is neglected. Moment capacities and places of plastic hinges are determined experimentally. Nail characteristics do not follow the Eurocode 5 [4] but rather the Danish timber codes.

5. Results and discussion
The experimentally determined load-bearing capacities of the connections were compared to the results from numerical simulations and analytical solutions.

Measured densities of tested angle brackets are presented in table 1.
Table 1. Evaluation of measured densities.

| Specimens          | Mean density ($\text{kg/m}^3$) | Standard deviation ($\text{kg/m}^3$) | Characteristic density ($\text{kg/m}^3$) |
|--------------------|---------------------------------|--------------------------------------|----------------------------------------|
| 05-21 - original   | 447.9                           | 32.1                                 | 386.3                                  |
| 05-21 - improved   | 424.2                           | 23.6                                 | 369.1                                  |

Compared to table densities in EN 338 [14] of timber strength class C24 ($\rho_{\text{mean}} = 420 \text{ kg/m}^3$, $\rho_k = 350 \text{ kg/m}^3$), 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.

| Mean capacity$^a$ ($\text{kN}$) | COV$^b$ ($\%$) | COV$^c$ ($\%$) | EN ISO 8970 | COV$^d$ ($\%$) | $k_{\text{cov}}$ ($\%$) |
|---------------------------------|----------------|----------------|--------------|----------------|-------------------------|
| 05-21 – original                | 12.324         | 7.16           | 12.41        | Not satisfied  | 15.99                   | 1.2881                   |
| 05-21 – improved                | 17.492         | 5.57           | 13.01        | Not satisfied  | 16.46                   | 1.2652                   |

$^a$ With transformed values to timber strength class C24
$^b$ COV$\rho$ is coefficient of variation of the measured wood density
$^c$ COV$\delta$ is coefficient of variation of the measured or the modified load-carrying capacity
$^d$ COV$R$ is coefficient of variation of the load-carrying capacity considering full variation of the wood density
$^e$ $k_{\text{cov}}$ is COV$R$ to COV$\delta$ ratio used in Standard deviation calculation according to EOTA TR 16 [7]

In both sets, there were samples which did not meet density conditions from EN ISO 8970 [8]. This fact resulted in a high value of factor $k_{\text{cov}}$ (see Table 2).

Load bearing capacities from the evaluated experiments were compared to the values calculated by analytical methods and by numerical modelling (see Table 3).

Table 3. Comparison of characteristic load-bearing capacities.

| Experiments ($\text{kN}$) | Analytically - elastic ($\text{kN}$) | Analytically - plastic ($\text{kN}$) | Numerically ($\text{kN}$) |
|---------------------------|--------------------------------------|--------------------------------------|---------------------------|
| 05-21 – original          | 8.50                                 | 6.56                                 | 4.04                      | 7.15                      |
| 05-21 – improved          | 11.67                                | 7.56                                 | 8.07                      | 8.63                      |

Load bearing capacity of each connection was experimentally 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.

Analytical elastic approach expected over 15% improvement of load bearing capacity of the connection and underestimated it. On the other hand, the plastic approach expected 50% improvement and overestimated it. From these results it is obvious that both methods are quite inaccurate.

The numerical approach gives more accurate results than the analytical approach. Characteristic values were determined by adding conditions to force displacement diagrams of nails (see figure 4) preventing nails from carrying higher force than their characteristic capacities.
Numerical simulations of the beam to beam connection also brought complete load-displacement curves for the studied connections using angle brackets. These results were compared to the experimentally determined force-displacement curves. The force represents the external load applied on the connection and displacement is measured considering opening of the gap between the beams in the connection.

In figure 11, mean behavior of the experimentally studied connection is compared to the simulated behavior of the connection using nail load-bearing capacities calculated considering the measured densities of timber used in each connection set.

![Figure 11](image)

**Figure 11.** 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 mean density of timber measured in tests.

As it is evident from the plots, both simulations match quite well with the experimentally studied behaviour until they started to behave nonlinearly. This quite high difference between mean load bearing capacities of the 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 induces a bending moment in the nails fixed in its holes. This bending moment increases the pressure of the 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 does not increase its withdrawal resistance, conversely, it reduces it due to the rope effect and the plastic motion.

6. Conclusions

The results presented show how to determine load bearing capacities of spatial connections using angle brackets in three different ways: by full-scale experiments according to the European Technical Reports, by an analytical method and by numerical modelling using simplified material and nail models. All determined load-bearing capacities were listed and compared.

Although the experiments are not dramatically expensive or time consuming, it is useful to have a cheaper, faster and reasonably reliable calculation procedure. The main benefit of the analytical solutions is that they are cheap. However, they are very conservative and their reliability is not well proved.

Numerical simulations provide more applicable results than the analytical solutions. Although numerical modelling of timber is still very challenging and numerical models were quite simplified, simulation proved to be a very useful tool for predicting the behavior of the whole connection and for optimizing the shapes of steel elements in the processed connections.
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