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EXPERIMENTAL AND NUMERICAL ANALYSIS OF STEEL JOINTS IN ROUND WOOD

Abstract

The paper analyses a drawn steel joint in round logs for which several types of reinforcements have been proposed. The load-carrying capacity of the reinforcements have been tested in laboratories. At the same time, numerical modelling has been performed - it has focused, in particular, on rigidity of the joints during the loading process. Physical and geometrical nonlinearities have been taken into account. The Finite Element Method and 3D computation models have been used in the numerical calculations.

Keywords

Wood, numerical model, slippage, 3D model, dynamics, block shear, stiffener.

1 INTRODUCTION

Timber structures and wooden structural elements rank among modern elements in architecture. Much attention is also paid to them in research [10]. Timber is also often combined with other materials [1] and [4]. When designing timber structures, it is advisable to focus on structural details [6] and [9]. Another important aspect is specification of timber properties [5]. Design of timber structures is governed by standardised procedures [2] and [3]. There are many publications which provide detailed steps for design and assessment of timber structures [7], [8] and [15]. In some cases, it is advisable to use the probabilistic approach, such as [11].

Internal forces in rod elements and structures are typically calculated in software applications which are based on the Finite Element Method. SCIA Engineer [14] or ANSYS [13] for advanced analyses are among software applications which are frequently used. In technical practice, ANSYS is not, however, efficient as it is too general. This software was not developed for standard design procedures. A steel joint in round log was chosen for the analysis and optimising process. Data from laboratory tests are available for that joint [12]. The joint is used in log buildings and often in structures in forests – look-out towers or in latticework bridges or footbridges.

If this type of joint is used in bridge and tower engineering, the joint is subject to dynamic loads which should be also considered in designs. The load capacity and behaviour of the joint is also considerably influenced by environment and quality of maintenance. For this reason, several

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types of reinforcements have been proposed for optimising of the behaviour and load capacity of the joint. The reinforcements were tested in the laboratory, numerically modelled and compared with each other. This paper summarises the results. The non-linear modelling focused on rigidity of the joint during the loading process. Physical and geometry nonlinearities were considered there. Results of the numerical modelling can be used then for design of neighbouring elements which form the structural whole with the joint.

2 JOINT DETAILS

Fig. 1 shows details of the joint without reinforcement. The joint connects round log with an internal steel plate. The joint is formed by steel bolts. The timber is sawn wood, C24. The steel is a steel plate, 8 mm thick, with the S235 grade. 20 mm dia. bolts are made from 8.8 steel. The timber section is formed by round log, 120 mm dia, with knots, seasoning splits and natural imperfections.

The steel is without any surface treatment.

The joint was fixed to the testing device by means of two 20 mm dia. bolts made from 8.8 steel. Or it was fixed into press jaws through a steel plate in the friction connection. The joint was tested in several institutions (ČVUT PRAHA, VŠB-TU OSTRAVA FAST, VÚD ŽILINA). The joints were tightened up. The bore hole was 20 mm in timber and 22 mm in steel. 20 mm bolts were made of 8.8 grade.

In the laboratory, the joint was loaded by dislocation of the press head. In the numerical model, the joint was loaded only by deformation and static forces. No numerical models were prepared for a dynamically loaded joint in real tests. In the numerical model the load was applied as deformation along 4 mm. Border conditions were adjusted to correspond most to the real fixing in the press. One end of the internal steel plate is fixed at the edge in all three directions of movement, while the other end is fixed only at right angle to the internal steel plate. The direction which is parallel to the axes of the round log and steel plate is free for the specified 4 mm movement (the shift results in tensile load of the joint).

Fig. 1 shows the technical scheme and description of the round log for both the numerical model and laboratory test. In this figure, the joint is not reinforced by elements at right angle to wood fibres. The produced and modelled joints in round log can be divided into three types:

1) type: TSK_1 - this is a joint without any reinforcement – see Fig. 1

There is no any reinforcement in the joint (Fig. 1) and the wood could split freely at right angle to the fibres. This joint is easy to make, but if close to the full load capacity the joint may become fragile if there is failure. Its ductility is low. Static load results in sudden failure of a specimen without any major plastic deformation in the joint.

2) type: TSK_2 - this is a joint reinforced by means of threaded bolts - the thread is along the entire bolt shaft. See Fig. 2.

The joint is reinforced by bolts. Bores are not pre-drilled. The thread is along the entire bolt shaft. The bolts are counterbored into the fibres. See Fig. 2. This joint is also easy and fast to make. This reinforcement should increase ductility and load-capacity of the joint. In case of extreme load, the split spreads at right angle to the fibres but the joint does not completely split because it is fastened by bolts and is still able to transfer the load. Four possible types of failure may occur in the joint: a) the bolts could tear away and wood could split b) block slippage could occur c) a wood component could break d) steel elements could plasticize or the wood wall compression may occur in the joint.

3) type: TSK_3 - the joint is reinforced with a steel band. See Fig. 3.

The joint is reinforced with a steel sleeve fixed around the round log. See Fig. 2. This joint is also easy and fast to make. This reinforcement should increase ductility and load-capacity of the joint. Four possible types of failure may occur in the joint: a) the sleeve could plasticize and tear away b) block slippage could occur c) a wood component could break d) steel elements could plasticize or the wood wall compression could occur in the joint. The steel sleeves were tightened in a laboratory prior to the text. No-prestressing is applied.

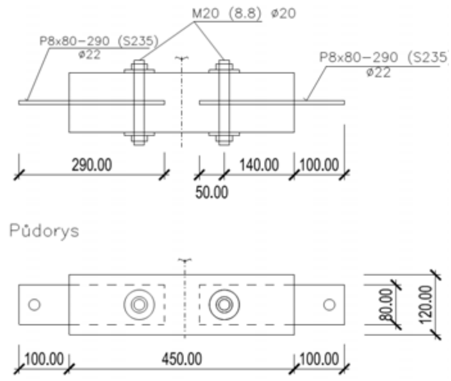

Fig. 1: Geometry of the joint in the round log without reinforcement, TSK 1

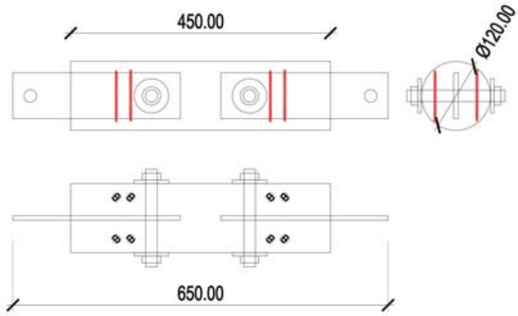

Fig. 2: Geometry of the joint in the round log, TSK 2

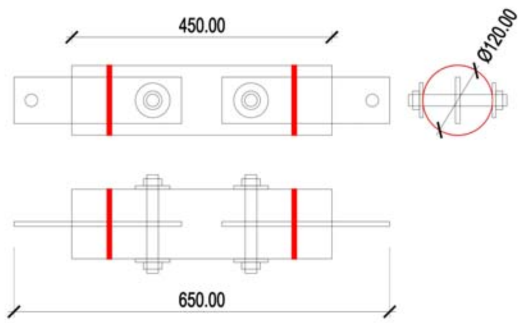

Fig. 3: Geometry of the joint in the round log, TSK 3

3 EVALUATION OF LABORATORY TESTS AND NUMERICAL MODELS

Total capacity of the tension joint with one bolt is calculated from (1) through (3). For the bolt under analysis, the load capacity for two shears is approximately 46.5 kN, while rigidity is 15.4 MNm^{-1} pursuant to DIN 1052 [2]. Calculation of rigidity was based on standardised characteristics of timber density which was corrected at 390 kgm^{-3} to be compliant with the joint under modelling. These are the characteristic values and are reduced, depending on duration of the load and environment where the load is located.

In case of a short-lasting load and environment #3, the approximate design values would be R_d = 25 kN and K_d = 7.40 MNm^{-1} for two shears per one bolt. If wood density is ρ_{520} = 520 kgm^{-3}, the characteristic slippage rigidity for two shears is K_{520} = 23.702 MNm^{-1}. In real joints the primary slippage rigidity after activation of a mechanical fastener in wood is 2 up to 2.5 times higher than the standardised value.

This fact should be considered when comparing the numerical values with tested data in joints. Slippage of the joint in round wood is shown in Fig. 4.

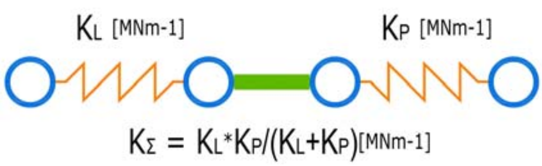

Fig. 4: Final rigidity of the joint

$$F = K_{ser} * \Delta, \qquad (1)$$

$$K_{ser} = \rho^{1.5} * \frac{d}{20} = 390^{1.5} * \frac{20}{20} = \underline{7701{,}88} \text{ N/mm}, \qquad (2)$$

$$R_k = f_{h,1,k} * t_1 * d * \left(\left(2 + 4 * \frac{M_{y,k}}{f_{h,1,k} * d * t_1^{\,2}} \right)^{0.5} - 1 \right) = \underline{23{,}25} \text{ kN}, \qquad (3)$$

F	– force depending on rigidity of the joint	[N]
K_{ser}	– rigidity of a single-shear joint	[Nmm^{-1}]
Δ	– dislocation of the joint in place of connection	[m]
ρ	– timber density = 390 kgm^{-3}	[kgm^{-3}]
d	– diameter of the fastener	[m]
R_k	– characteristic rigidity of a single-shear joint	[kN]
$f_{h,1,k}$	– characteristics strength in timber compression	[MPa]
t_1	– compression length per bolt shear	[m]
$M_{y,k}$	– plastic moment of load capacity of the fastener	[Nmm]

Fig. 5 shows the tension testing of a joint in round log. Four specimens were tested. Tests were carried out in the Faculty of Civil Engineering, VŠB - Technical University of Ostrava. Fig. 6 and 7 show the specimens prepared for laboratory tests. The curves recorded by the testing device show clear slippage before activation of the bolt. This proves an increase in rigidity of the joint.

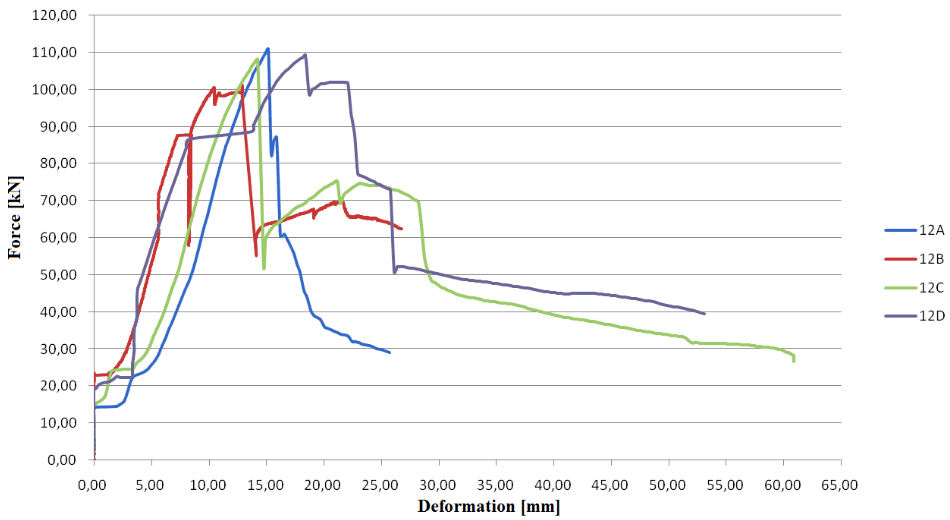

Fig. 5: Round wood #9, humidity: 12 %, density: ca 530 kg/m^3,
(A-D identifies the laboratory tests of that type of joint)

The charts end when fragile failure occurs in timber. This is caused by the character of timber which is a natural material as well as by the fact that fragile failure occurs in timber if parallel tension and tension at right angle to fibres are applied and load capacity is exceeded. Fragile failures occur also if timber is in shear. The tests indicate that a steel band cannot increase load capacity of the joint. Before fatal failure of the specimen occurs, the steel band is, however, able to resist, for a certain time, the load which is at limit of failure of non-reinforced round wood.

Fig. 6: Test – round wood # 9, humidity: 12 %, density: ca. 520 kg/m³

Fig. 7: Test – round wood # 11, humidity: 12 %, density: ca. 530 kg/m³

Fig. 8 shows results of laboratory tests in joints made in round wood. Four specimens were tested. Numerical models with various material parameters were prepared on the basis of the laboratory tests. Considering an orthotropic model of timber, bilinear stress-strain curves were used. A bilinear strain-stress curve was also used for steel in joints.

Fig. 9 through 12 show graphic results of the numerical model for TSK 1. This is a model of a joint without any reinforcement. The purpose of the model was to adjust properties of the material for the other numerical models: TSK 2 and TSK 3. Fig. 8 shows that the bolts are able to increase the load capacity and, in turn, ductile behaviour of the joint.

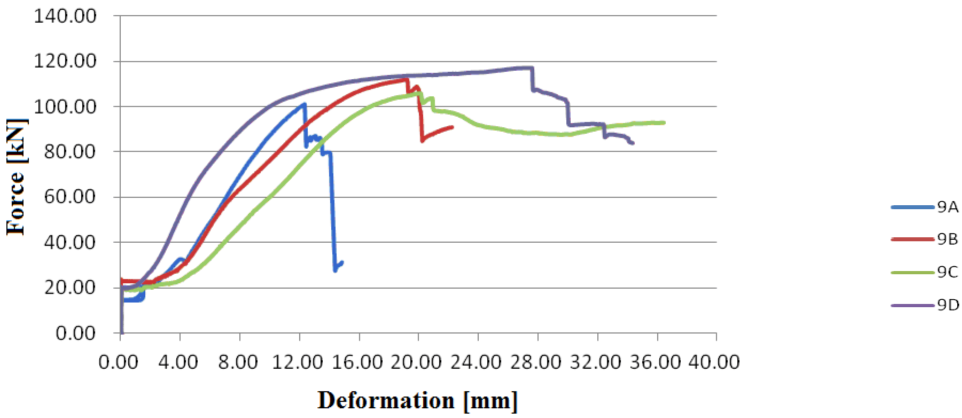

Fig. 8: Round wood #9, humidity: 12 %, density: ca 520 kg/m³, (A-D identifies the laboratory tests of that type of joint).

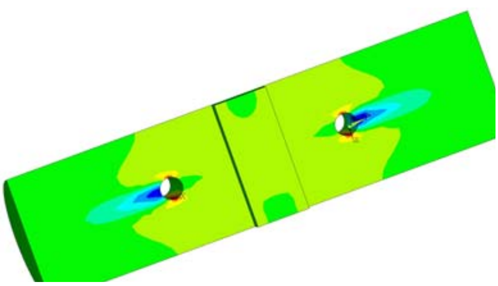

Fig. 9: Stress parallel to fibres: -77 and +74.528 MPa, model TSK 1 (F=81.620 kN)

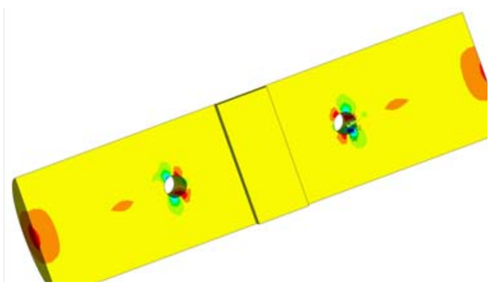

Fig. 10: Stress at right angle to fibres: -7.597 and +3.009 MPa, model TSK 1 (F=81.620 kN)

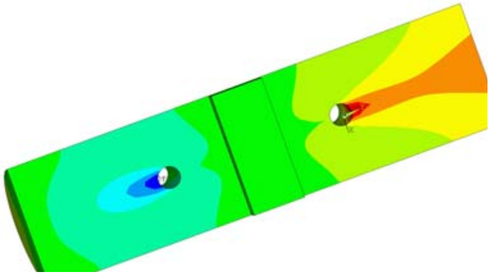

Fig. 11: Horizontal deformation of the model: 1.256 mm, TSK 1 (F=81.620 kN)

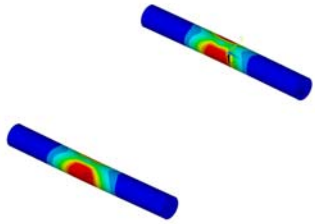

Fig. 12: von Misses stress: 648.34 MPa, TSK 1 (F=81.620 kN)

Fig. 13 through 16 show graphic results of the numerical model for TSK 2. This is a model of a joint which is reinforced by bolts bolted at right angle to the fibres. This solution provides the best results. That reinforcement is recommended because it is efficient and easy to perform. The bolts fasten directly the wood and some tension which is applied at right angle to the fibres is transferred directly into the bolts. The bolts are ductile and may transfer big tensile forces and some bending effects. The bolts are easy to install. They are protected against weather and do not impair the diameter (unless pre-drilled and unless their diameter exceeds 6 mm). The reinforcement is fire resistant. As is not visible from the outside, it is not disruptive. Using the bolts is among the efficient standard reinforcements used for tension which is applied at right angle to the fibres.

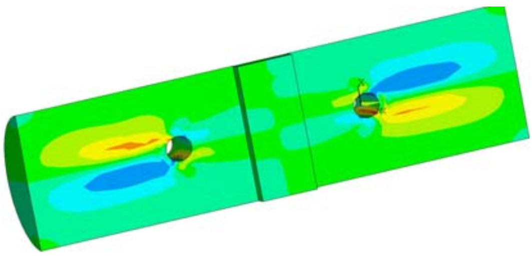

Fig. 13: Shearing stress, 9.7 MPa, model TSK 2 (F=115.942 kN)

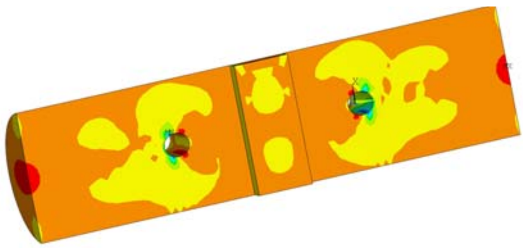

Fig. 14: Stress at right angle to fibres, -18.887 and +3.676 MPa, model TSK 2 (F=115.942 kN)

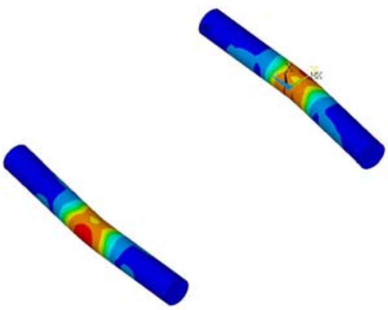

Fig. 15: von Misses stress: 703 MPa, TSK 2 (F=115.942 kN)

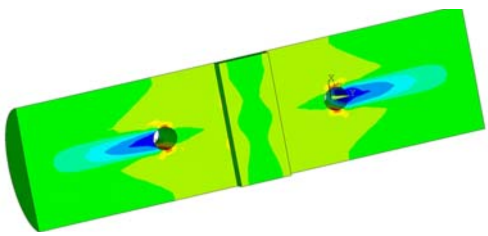

Fig. 16: Compressive stress parallel to fibres: -89.57 and +80.26 MPa, model TSK 2 (F=115.942 kN)

Fig. 17 and 18 show the finite element grid of the numerical models. Fig. 19 shows the shearing stress in the timber volume. Fig. 20 shows the stress applied at right angle to the fibres.

A steel band used in TSK3 did not improve the situation considerably. Because the timber splits once tension is applied at right angle to the fibres, this load is not suitable. The failure occurs in the timber volume and the steel band is not able to resist the stress applied at right angle in the fibres. This means, the steel band is not able to reinforce the joint efficiently. In order to make the band efficient, it is necessary to activate them before the tension. But this is not possible in standard practice. The reason is deletion of pre-stress by releasing the anchor, changes in temperature and major changes in timber volume which are caused by humidity. That is why this type of reinforcement is not efficient enough for the joint.

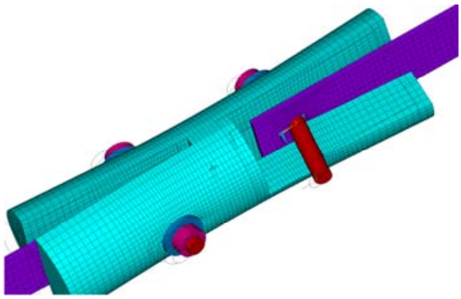

Fig. 17: Detail of deformation in the joint

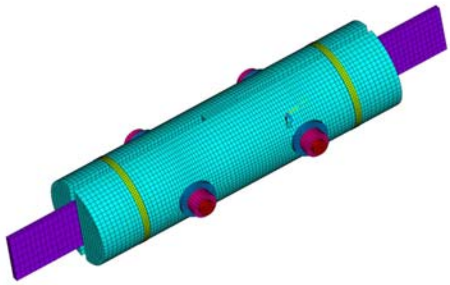

Fig. 18: Numerical model TSK 3

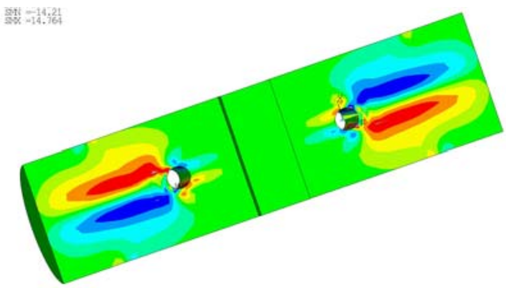

Fig. 19: Shearing stress, 7 MPa, model TSK 3 (*F*=113.21 kN)

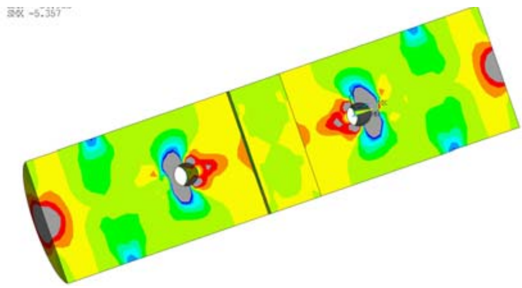

Fig. 20: Stress at right angle to Fibres, -4 and +2 MPa, model TSK 3 (F=113.21 kN)

Fig. 21 shows the splitting failure for the test with the steel bands, TSK 3. It also shows the numerical models with the finite element mesh and the inside view at the deformed bolts plus total global deformation of the joint.

The numerical models were calculated with geometric and physical nonlinearities. Orthotropic properties of timber and contact nature of the joints were taken into account. Fig. 22 shows the numerical results for the tested models of round log. The calculation was performed in several variants: SG, BV, SB and SGN for the recommended parameters of anisotropic reinforcement in the model.

The results of the numerical tests correlate well with the laboratory tests. The maximum load capacity in the numerical model TSK 1 (without any reinforcement) was 82 kN. The maximum load capacity for TSK 2 (with bolts) and TSK 3 (with a steel band) was approximately 112 kN. These values correspond with the real tests done in the round wood.

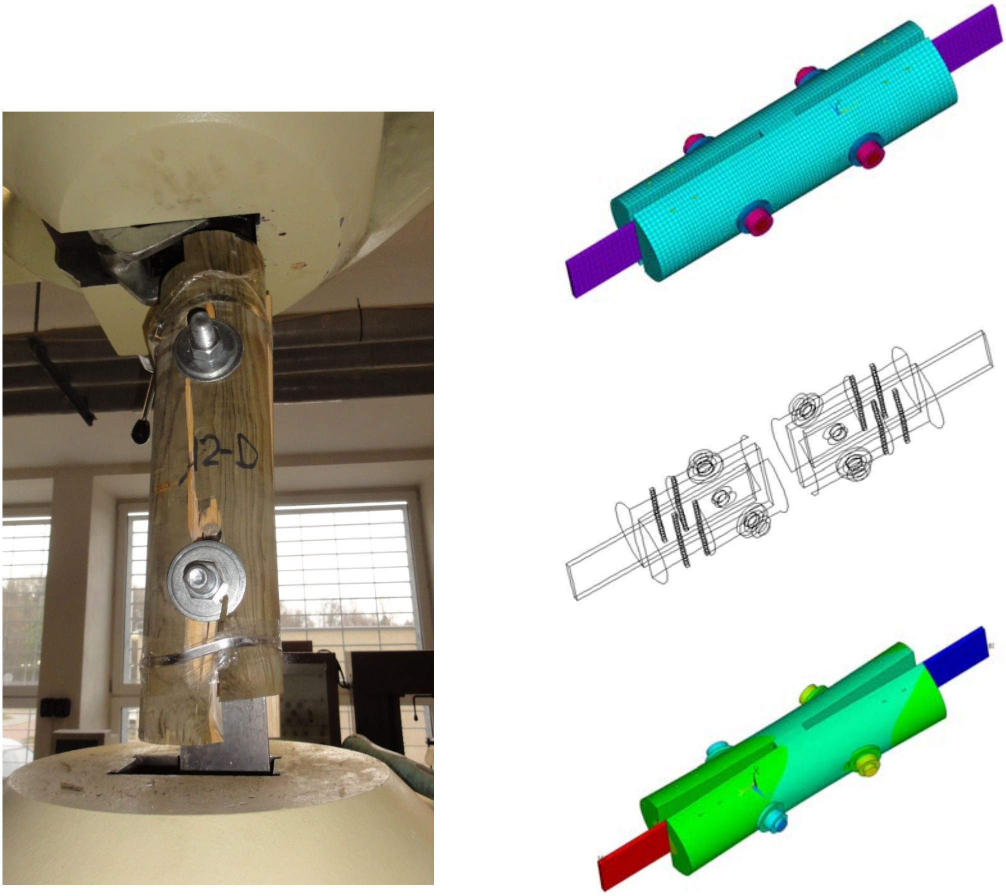

Fig. 21: The tested specimen reinforced with a band, and a numerical model with a bolt

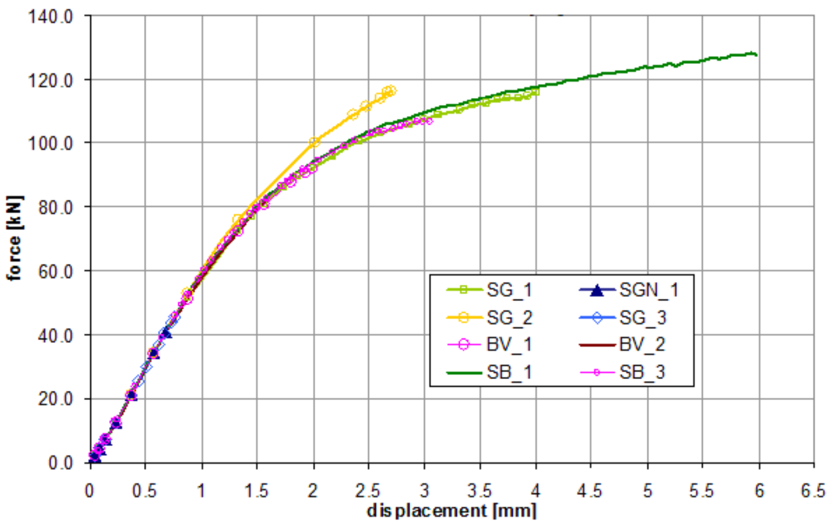

Fig. 22: The numerically tested models of round wood in ANSYS (SG, BV, SB and SGN for the recommended parameters of anisotropic reinforcement in the model)

The numerical model behaves in a stable manner until the specified deformation of ca. 4.0 mm is reached. With higher deformations, the steel bolt plasticizes, compression occurs in the bolt bore, and the timber splits by the compression applied at right angle to the fibres.

The numerical models also need to be verified by laboratory tests of both the joints and materials.

4 CONCLUSION

Having analysed the experimental and numerical results, the following conclusion can be drawn: the maximum obtainable load capacity of each type of reinforcement are very same in the mathematical models and in data obtained by experiments. In initial rigidity, such compliance is also good. It is, however, necessary to keep in mind that the slippage was different for the test models of the joints. The numerical models did not take the slippage into account because the slippage is various and material properties and production tolerances are very different for each type of joint used in the timber part of the round wood.

The comparison was performed for statically loaded joints only. Total deformation in tests is higher than in data obtained in the numerical models. The reason is the slippage which might be considerable because of bores, or that the material is natural wood.

Finally it should be pointed out that the results of the numerical modelling are close to the values obtained in the laboratory tests. Using the numerical models it is possible to pre-optimize the reinforcement and identify shear stress and critical areas where high stress is cumulated, in particular in places where the stress is applied at right angle to the fibres.

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