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ДРУШТВО НА ГРАДЕЖНИТЕ КОНСТРУКТОРИ НА МАКЕДОНИЈА
Партизански одреди 24, П.Фах 560, 1001 Скопје
Северна Македонија

MASE
MACEDONIAN ASSOCIATION OF STRUCTURAL ENGINEERS
Partizanski odredi 24, P. Box 560, 1001 Skopje
North Macedonia

NA - 14

mase@gf.ukim.edu.mk
http://mase.gf.ukim.edu.mk

NUMERICAL MODELLING OF END-NOTCHED GLULAM BEAMS REINFORCED WITH SCREWS

Marija TODOROVIĆ[1], Ivan GLIŠOVIĆ[2], Boško STEVANOVIĆ[3]

ABSTRACT

Load carrying capacity of solid timber and glued laminated timber (glulam) beams is significantly decreased if there are notches made at the supports. Sudden change in cross-section height (notch) results in deviation of stresses leading to concentration of tension perpendicular to grain and shear stress in a notch corner, which causes crack opening and its growth. With load increasing, uncontrollable crack growth due to low resistance in shear and tension perpendicular to grain of wood, as well as brittle failure mechanisms as a result of these actions, can lead to failure of a beam. Therefore, notches should generally be avoided, and when unavoidable, notches should be reinforced. This paper presents a finite element based numerical investigation of bending behaviour of end-notched glulam beams reinforced with traditional screws for timber. Commercial software Abaqus was used for modelling of reinforced end-notched glulam beams subjected to bending. Cohesive Zone Modelling (CZM) was employed to simulate the crack growth phenomenon. Cohesive behaviour in the fracture region was defined through appropriate traction-separation law, while failure of elements was characterized by a progressive degradation of material stiffness which is driven by a damage process. Verification of the proposed model was performed through comparison with experimental tests. Good agreement was found between numerical and experimental results, proving that the developed model is successful in predicting the behaviour of reinforced notched timber elements. The numerical modelling, as well as the experimental research, can help in better understanding of the crack initiation and crack growth phenomenon in reinforced end-notched timber beams. Also, effectiveness of screws as reinforcement od end-notched glulam beams has been proven. Initial cracking of the notch corner cannot be prevented by the reinforcement. However, by placing screws uncontrollable crack growth was limited and load-carrying capacity and deformability of beams were increased.

The presented model can be used for further parametric analyses, which would include varying the loading configuration, geometry, material properties and types and positions of reinforcement. In addition, results obtained from FEM modelling can be useful in developing appropriate analytical design models for reinforced end-notched timber elements.

Keywords: *Glulam; Beam; Notch; Screws; FEM;*

[1] Assist. PhD, Faculty of Civil Engineering, University of Belgrade, Belgrade Serbia, todorovicm@grf.bg.ac.rs
[2] Assoc. Prof. PhD, Faculty of Civil Engineering, University of Belgrade, Belgrade Serbia, ivang@imk.grf.bg.ac.rs
[3] Prof. PhD, Faculty of Civil Engineering, University of Belgrade, Belgrade Serbia, bole@imk.grf.bg.ac.rs

1. INTRODUCTION

Notches made in solid timber and glued laminated timber (glulam) beams are very common in structural engineering practice, especially at the supports. Since these reductions in height represent weak spots in structures, it is advisable to avoid them altogether. However, there are various situations when beam notching is defined by architectural design of a structure and therefore necessary. Adequate reinforcement of notched beams is advisable in these cases.

The load carrying capacity of timber beams is considerably reduced as a result of stress concentration around the notch. Notches made on the tension side induce tensile stresses perpendicular to grain which, accompanied by shear stresses, can cause longitudinal splitting typically starting at the notch corner (Fig. 1). Cracks are unattractive appearance from aesthetic point of view, but are also very dangerous from structural perspective because crack propagation as the load level increases can lead to a failure of a beam. Reinforcement of such members is a cost-effective alternative for enhancing the load carrying capacity of structures in service. Traditionally, screws are widely used in timber and glulam connections. They are economic and time-efficient solution for reinforcement and they can be easily applied which is the reason why they were chosen in this study.

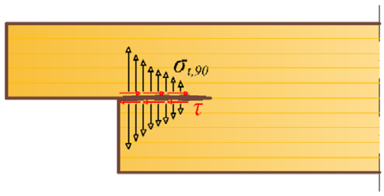
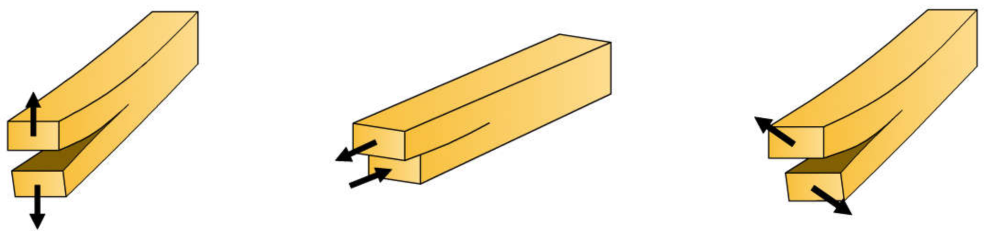


Fig. 1. Stress concentration at the notched end of a beam

The stress state at a crack can be described by different fracture modes. Mode 1 is a tensile opening mode characterized by separating of crack surfaces in the direction that is perpendicular to them - Fig. 2(a). Mode 2 represents in plane shear mode where crack surfaces slide one over the other - Fig. 2(b). The combination of the previous two modes is a mixed mode fracture, as shown in Fig. 2(c). Although both stresses (shear and tension perpendicular to grain) appear, crack opening is an apparent failure mechanism of a notch and it is caused by tension perpendicular to grain. Therefore, Mode I fracture is the most common failure mode of end-notched timber beams [6]. However, shear component usually exists and it should be also taken into consideration, especially in the case of reinforced beams.



a) Mode 1 fracture b) Mode 2 fracture c) Mixed mode fracture

Fig. 2. Fracture modes [2]

In the past decades, many researchers have dealt with notched timber beams. Fortino et al. [1] explained FEM simulation of Mode 1 cohesive crack growth in glued laminated timber. Jockwer [2] gave a thorough analysis of different design approaches of both unreinforced and reinforced notched beams. Franke, Franke, & Harte [3] dealt with methods of repair of structural performance of timber beams, including the ones with notches. Oudjene et al. [4] showed a numerical approach for modelling both unreinforced and reinforced notched beams. Dietsch [5] talked about the necessity of new design approaches of strengthened timber beams, including strengthening of notches, and implementation of these in a new section of Eurocode 5.

This paper presents a FEM modelling approach dealing with bending behaviour of screws reinforced end-notched glulam beams. A 3D finite element model was developed in software package Abaqus. The numerical methodology used cohesive damage modelling. Experimentally obtained results were used for the verification of numerical simulation based on the comparison of failure mode, load-deflection relationships, stiffness and ultimate load carrying capacity. The numerical results showed that the proposed model is adequate for predicting progressive damage of reinforced notched timber beams.

2. EXPERIMENTAL RESEARCH

The experimental research was conducted at the Laboratory of Structures, Faculty of Civil Engineering, University of Belgrade. Ten reinforced (Series R) notched glulam beams were tested in bending to the point of failure. Since this research was a part of a larger experimental investigation, five unreinforced (Series U) beams were used as a control series. Reinforcing was performed with screws. Five reinforced beams had screws installed perpendicular to beam axis (Series R-s90) and five had screws positioned at an angle of 45° to beam axis (Series R-s45).

2.1. Material and method

The glulam beams were made from spruce timber classified in the strength class GL22h according to EN 338 [7]. Before the tests were performed, the beams were conditioned at a temperature of T = 20±2º C and a relative humidity of RH = 45±5 %. After testing, moisture content was measured in each beam using a digital hygrometer at different locations. The moisture content in tested beams was about 11.5%.

The overall length of the beams was 4000 mm and the cross section was 100 x 220 mm. Each beam was composed of seven 32 mm thick laminations. At the notched ends, the height of the beams was reduced to 110 mm (by half) and the length of notches was 250 mm. The reinforcement selected in this study was traditional screws for timber (Fig. 3) with a diameter 10 mm and length of 200 mm for Series R-s90 and 250 mm for Series R-s45. Threaded part of screws was 125 mm and 160 mm, respectively. According to the manufacturer the steel grade of screws was 5.6. Two screws in one row were positioned near the both notched ends of the beams. The requirements for minimal screw edge distances and spacing were satisfied while keeping the reinforcement as close as possible to the notch corners.

Fig. 3. Screws used as reinforcement

All the beams were subjected to bending test in accordance with EN 408 [8]. The beams were tested in four point bending configuration over a simply supported span of 3750 mm. The distance between two loading points was 1350 mm, while the distance from the loading points to the supports was 1200 mm. A schematic illustration of the bending test configuration is shown in Fig. 4.

The specimens were supported on roller bearings at the ends. Roller bearings were also used at the load application points. The effects of local indentation at both the load application and support positions were minimized by placing steel plates. The load was applied monotonically until failure using a hydraulic jack and recorded with a compression load cell and it was transformed from one point to two points with a steel beam. The monotonic load was applied at a stroke-controlled rate of 4 kN per minute so as to cause the failure of the unreinforced beams in approximately 5 minutes. The reinforced beams were tested with the same load rate in order to ensure a fair comparison of test results. The failure of the reinforced beams was achieved in about 10 minutes. Linear variable differential transducers (LVDTs) were used for the measurement of mid-span deflection of the beams as well as the measurement of crack opening in notch details. The deformation data from LVDTs and corresponding load data from a loading cell were recorded by a computerized data acquisition system. Self-weight of hydraulic jack and steel beam were added to the recorded load. This additional load was 1.3 kN. The typical test set-up is shown in Fig. 5.

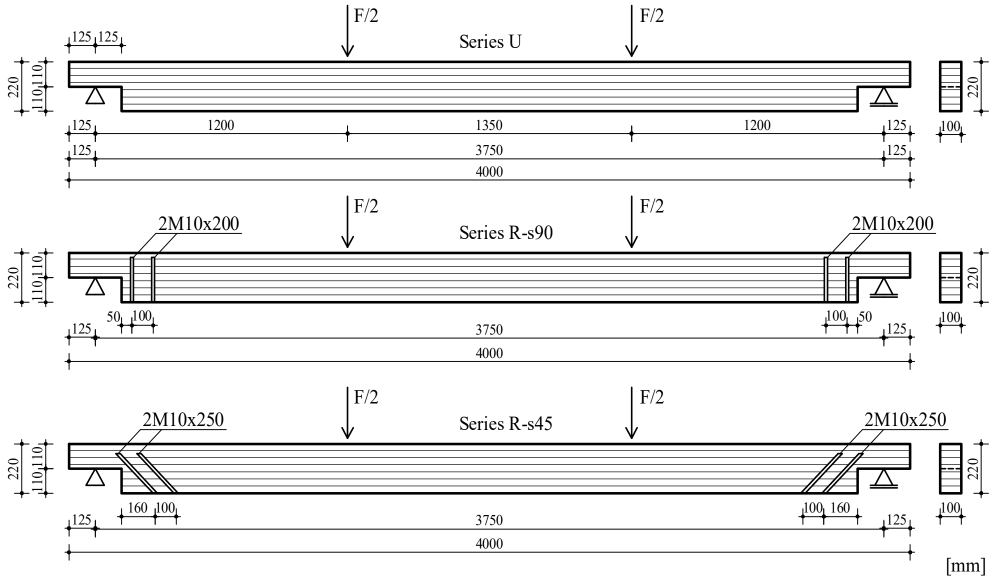


Fig. 4. Geometry and loading of the beams

Fig. 5. Experimental test set-up

When considering the specimens that were going to be reinforced special attention was put into screws installation. The preparation of Series R specimens is shown in Fig. 6. The holes for screws were pre-drilled very carefully to a diameter of 8 mm, with approximate drilling length of 200 mm and 250 mm. The screws were installed using a moment wrench.

Fig. 6. Preparation of reinforced specimens

2.2. Test results

The effects of the notches on the mechanical properties of glulam beams are significant. All tested unreinforced beams (Series U) exhibited linear load-deflection behaviour until the point of failure. The beams failed at the notch details due to excessive tensile stress perpendicular to grain. Crack opening (Mode 1 fracture) at the notch corner was the obvious failure mechanism of unreinforced notched beams. Due to brittle nature of wood behaviour in tension and in shear, failure of Series U beams was sudden without warning signs. Prior to ultimate load, only very little crack opening was observed. After the development of initial crack at the notch corner, uncontrollable crack growth occurred.

Reinforced notched beams (Series R) essentially experienced linear behaviour up to the point of failure. Nine out of ten beams failed in a brittle way. Although ultimate load was improved, the reinforcement was not enough to change the failure mode from combined tensile perpendicular to grain and shear to bending failure. Despite the reinforcement intervention, initial cracking of the notch corner cannot be prevented. It was observed that crack initiation started at relatively low loads, which corresponded to unreinforced beams load at failure. Excessive crack opening was limited by the reinforcement. With further loading the stable crack growth was accompanied by sharing of the crack. At failure, unstable crack growth occurred and crack shearing increased considerably. It can be assumed that the shear failure was dominant failure mechanism (Mode 2 fracture). In most cases, failure was accompanied by withdrawal of the screws.

At the notch corner vertical reinforcement screws were subjected to combined loading parallel and perpendicular to the shear plane. There were clear plastic deformations in the reinforcement indicating that plastic hinge was formed in the fracture region in the case of these beams. The idea of inclined screws was to load the reinforcement axially (in tension), the direction in which they demonstrate the highest stiffness. Therefore, Series R-s45 beams were expected to have higher load carrying capacity, but due to insufficient penetration length of the screws, they failed even earlier than the beams from Series R-s90. Since conventional screws require pre-drilled holes for installation, better results could be achieved with self-tapping screws for reinforcing and strengthening of timber structures.

Results of experimental tests in terms of load carrying capacity, deformability and stiffness for all beam series are given in Table 1. The ultimate load was taken as a maximum force, which caused failure of the beams. The mid-span deflection was taken as a value that corresponded to the ultimate load. The bending stiffness was calculated from liner part of the load-deflection curve of each beam.

Table 1. Experimental results

Beam	Ultimate load F (kN)	Mid-span deflection for ultimate load w (mm)	Bending stiffness EI (kNmm^2 x 10^8)
Series U			
U6	15.0	13.8	9.03
U7	12.7	12.1	8.85
U8	16.7	15.1	9.55
U9	10.7	8.8	9.91
U10	8.7	8.0	8.60
Average	12.8	11.5	9.19
SD	3.2	3.1	0.53
CV	25.2	26.6	5.8
Series R-s90			
R1-s90	42.7	47.7	8.46
R2-s90	29.8	27.8	10.46
R3-s90	36.3	39.7	8.63
R4-s90	37.0	110.4	9.32
R5-s90	34.0	39.2	9.14
Average	35.9	52.9	9.20
SD	4.7	32.9	0.79
CV	13.0	62.1	8.5
Comparison to Series U (%)	180.5	360	-
Series R-s45			
R1-s45	38.0	40.1	9.01
R2-s45	36.7	40.8	8.29
R3-s45	34.6	38.9	9.19
R4-s45	30.0	59.1	8.54
R5-s45	31.1	32.6	8.83
Average	34.1	42.3	8.77
SD	3.5	9.9	0.36
CV	10.1	23.5	4.1
Comparison to Series U (%)	166.4	267.8	-

SD – Standard deviation; CV – Coefficient of variation

The unreinforced notched beams (Series U) had an average ultimate load of 12.8 kN. The load carrying capacity of the beams was considerably reduced due to presence of notches. Introduction of reinforcement at the notched ends of the beams resulted in improvement in load carrying capacity. The reinforced beams obtained an average ultimate load of 35.9 kN and 34.1 kN, for screws positioned at the angles of 90° and 45°, respectively. All reinforced beams showed an increase in ultimate load when compared to the loads recorded for the beams without reinforcement. This increase was 180.5 % and 166.4 %. Unreinforced notched beams completely lost their load carrying capacities after the first crack developed. On the other hand, reinforced beams continued to carry the load after initial cracking. However, insufficient penetration length didn't allow for the reinforced beams to fail in bending, since screws withdrawal occurred before the beams reached the load carrying capacity of beams without notches.

The reinforced beams underwent large deformations before the failure when compared to the unreinforced ones. Average measured mid-span deflection at ultimate load was 52.9 mm, 42.3 mm and 11.5 mm for beams of Series R-s90, Series R-s45 and Series U, respectively. At failure, the reinforced beams exhibited in average 3.6 - 4.6 times larger mid-span deflections. Hence, screws helped improve the deformability of the beams.

All the beams had similar bending stiffness values. This was expected since the applied reinforcement was not meant to improve the bending stiffness. Series R-s45 had a bit lower value which can be explained by the variability in timber properties that generally exists when this material is in question.

3. NUMERICAL MODELLING

Numerical modelling of notched glulam beams reinforced with screws was performed using the commercial multi-purpose finite element software Abaqus ver. 6.13 [9].The crack opening and its growth in glulam specimens subjected to short-term loading was simulated using a nonlinear fracture mechanics approach via Cohesive Zone Modelling (CZM) option.

3.1. Numerical approach for cohesive crack propagation in wood

During the performed bending tests on unreinforced samples, the cracks were initiated within the notch detail of beams and they propagated in the grain direction under fracture Mode 1. Since the crack propagation path is known from experimental testing, the fracture region can be adequately described by Cohesive Zone Modelling (CZM). Cohesive behaviour in the fracture region can be defined through appropriate traction-separation law, while failure of elements is characterized by a progressive degradation of material stiffness which is driven by a damage process, as it is described in the paper by Todorovic et al [10].

3.2. Model development

Standard solver of Abaqus was employed for 3D numerical analysis of tested beams. Geometry, loading and boundary conditions correspond to experimental testing layout, shown in Fig. 4. Due to symmetry in geometry, loading and boundary conditions, only half of the beam was considered while the removed parts were replaced with appropriate symmetry constraints. Each lamination was modelled as separate part. A perfect connection was assumed to exist at bonding interface between the laminations, because no bond-line failures were observed in the test specimens. Since the adhesive layer is very thin and not important for this FEM analysis, it was not included in the model. Steel plates at supports and loading points were also incorporated in the model.

All timber parts were modelled as C3D8R finite elements (eight-node solid finite elements with reduced integration). Steel plates were modelled as S4R finite shell elements. Screws were modelled as one-dimensional beam elements with appropriate radius. Modelling of screws in a form of three-dimensional solid elements significantly complicates and slows down the numerical analysis, and it is recommended that a simpler approach - screws as beam elements, be adopted [4]. In numerical modelling, the ideal connection between reinforcement and wood was assumed. The embedded region option (same as rebars modelling in reinforced concrete elements) was used to place reinforcement within the beam, with screws as “the guest” and timber beam as “the host” region. Fig. 7 shows reinforced end-notched glulam beams models.

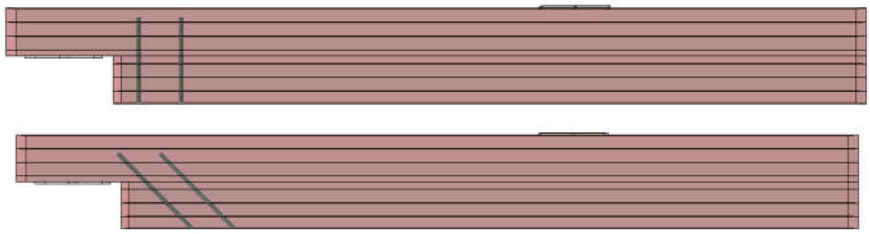


Fig. 7. FEM model of end-notched beams reinforced with screws

Finite element mesh used for the analysis is shown in Fig. 8. The mesh consisted of two finite elements through the thickness of each timber lamination (16 mm). The bonding interfaces were modelled by multi-point constraint (contact pairs), using “Tie” option. Surface-based cohesive behaviour available in Abaqus was chosen to model the fracture process region. To simulate the cohesive crack growth in wood, a damage initiation criterion of maximum nominal stress and a fracture energy-based damage evaluation criterion with exponential softening were used.

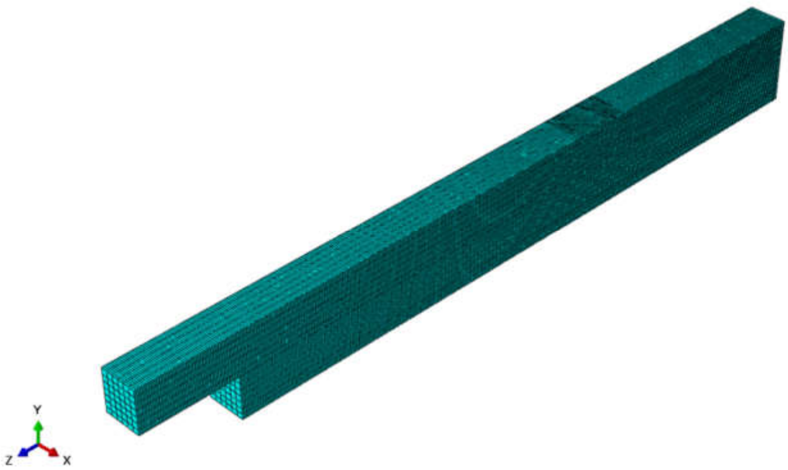


Fig. 8. Finite element mesh

Execution of the model involved a static small displacement analysis which consisted of a series of vertical displacement-controlled increments applied at the loading plate.

3.3. Material characterization

Adequate modelling of each material is very important for achieving accurate predictions from the numerical model.

Wood can be considered as an orthotropic linear-elastic material. It has three orthogonal directions of material symmetry: L (the longitudinal direction of fibres), R (the radial direction of rays) and T (the tangential direction to the annual rings). Nine independent constants are needed to describe the elastic behaviour of wood: three modulus of elasticity (E_L, E_R, E_T), three shear modulus (G_{LR}, G_{LT}, G_{RT}) and three Poisson’s ratios (ν_{LR}, ν_{LT}, ν_{RT}). The wood material parameters used for the analysis are listed in Table 2. Screws were modelled as elastoplastic material with modulus of elasticity E = 210 GPa, Poisson’s ratio ν = 0,3, yield stress f_y = 300 MPa and tensile strength f_u = 500 MPa, as defined by the manufacturer.

Table 2. Wood material properties [11]

E_L (N/mm²)	E_R (N/mm²)	E_T (N/mm²)	E_{LR} (N/mm²)	E_{LT} (N/mm²)	E_{RT} (N/mm²)	ν_{LR} (-)	ν_{LT} (-)	ν_{RT} (-)
10 750	860	538	768	724	77	0.37	0.42	0.47

The crack growth was studied in the RL propagation system, where the first letter indicates the direction perpendicular to the crack plane and second letter refers to the direction of the crack propagation. By referring to the notation used in Abaqus, the interface stiffness (K_{nn}, K_{ss}, K_{tt}), the cohesive strengths (σ_n, σ_s, σ_t) and the fracture energy (G_f) are input data in the damage model. The cohesive strengths were obtained through own experimental research. In the absence of experimental results, the interface stiffness parameters were chosen based on values given in literature for spruce timber. Several analyses are conducted for different combinations of cohesive parameters in order to choose the values to be used for the optimal interpretation of the experimental load-displacement curves. The adopted cohesive parameters are summarized in Table 3.

Table 3. Cohesive model parameters

K_{nn} (N/mm^3)	K_{ss} (N/mm^3)	K_{tt} (N/mm^3)	σ_n (N/mm^2)	σ_s (N/mm^2)	σ_t (N/mm^2)	G_f (-)
20	20	20	1.15	5.85	5.85	0.45

4. RESULTS AND DISCUSSION

Numerical results were compared with experimental ones in order to verify the proposed numerical model. The global responses of the beams in terms of load versus mid-span deflection obtained from experiments and from numerical analysis are shown in Fig. 9. The load-deflection behaviour predicted by the finite element model for reinforced notched beams demonstrates good agreement with the experimentally determined behaviour. Simulated behaviour was generally linear elastic up to failure which replicated the behaviour of experimentally tested beams.

Failure of reinforced beam was defined as a point when the crack propagates passed the second screw which corresponds to screws withdrawal in experimental testing. Comparison between the numerical and experimental failure modes is shown in Fig. 10. It can be seen that predicted failure mode is similar to the experimental one. High tension perpendicular to grain caused crack initiation. The screws limited excessive crack opening and notches failed in shear with dominant fracture Mode 2.

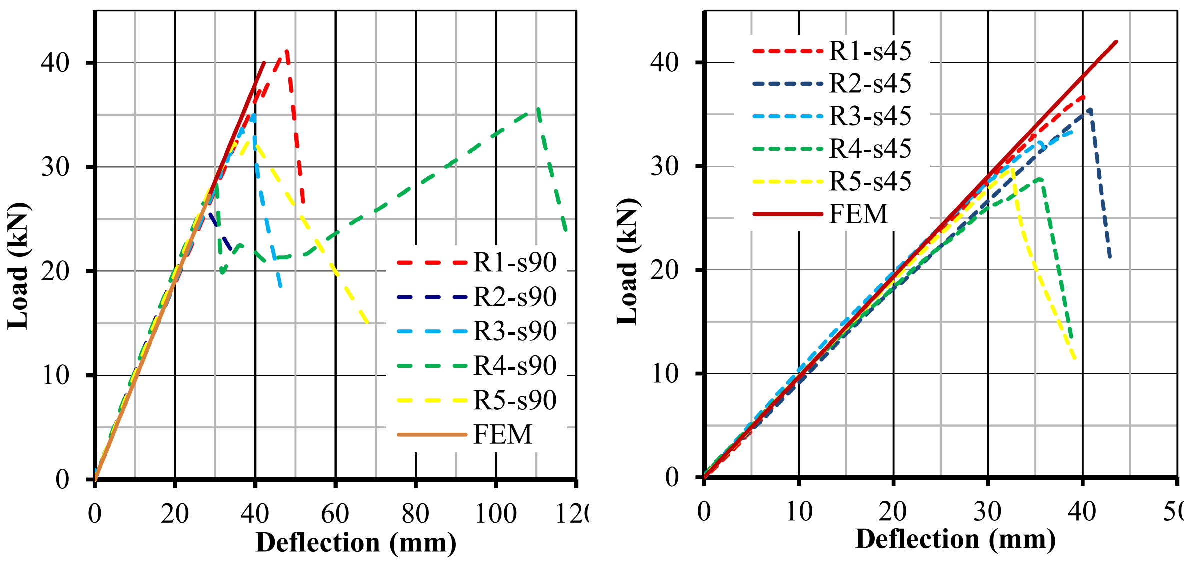


Fig. 9. Numerical and experimental load-deflection curves of end- notched beams reinforced with screws

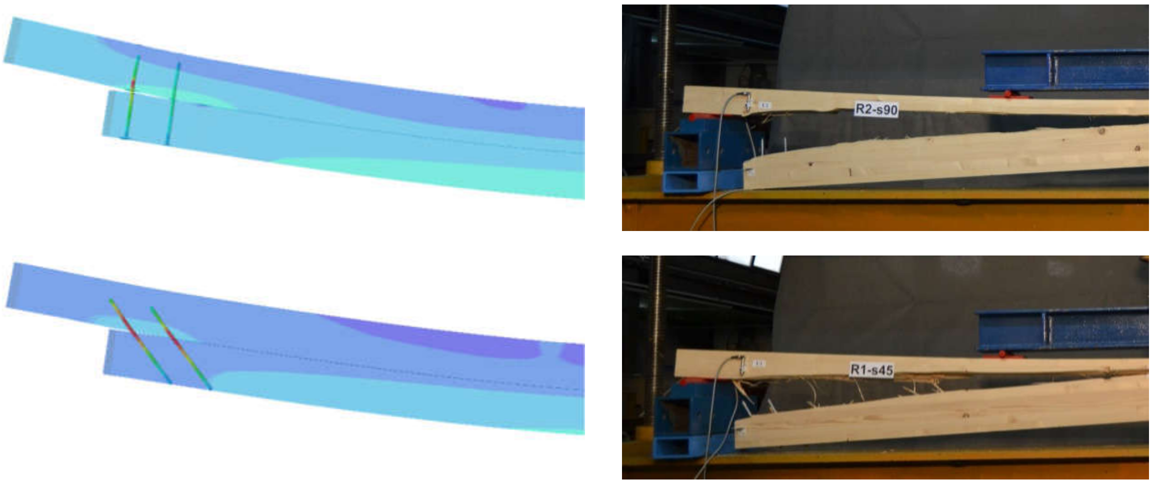


Fig. 10. Failure of end-notched beams reinforced with screws

The predictions of ultimate moment capacity, bending stiffness and deflection at failure obtained from the finite element model are compared with results from the experimental tests in Table 4. Average values are given for the experimental results. The numerical results of ultimate load carrying capacity for R-s90 Series indicate that the theoretical and experimental values are relatively close. The predicted value of the maximum load was higher than the experimental value. Considering the influence of knots and other defects in timber, the error is expected. In case of Series R-s45 beams this difference is even higher due to the fact that insufficient penetration length of screws caused premature failure in experimental tests. Numerical prediction of bending stiffness agreed well with experimental results. The variability in elasticity modulus of timber laminations was the reason for deviation between numerical and test results. The numerical model underestimated the mid-span deflection at failure of R-s90 beams (difference of about 20 %). This can be explained by the fact that one of the tested beams had extremely high deflection in comparison to others. Also, accurate screws withdrawal mechanism was not modelled.

Plastic deformation of screws that happened during the experiments was also noticeable in numerical models. The second screw in a row was activated only once the crack path had reached it. Therefore, better results could be achieved with positioning the screws one next to the other in the cross section.

Table 4. Comparison of experimental and numerical results

	Ultimate load F_{max} **(kN)**	**Mid-span deflection** w **(mm)**	**Bending stiffness** EI **(x 10^8 kNmm^2)**
		R-s90	
Experiment	35.9	52.9	9.20
FEM	40.0	42.1	8.76
Difference (%)	11,4	20.4	4.8
		R-s45	
Experiment	34.1	42.3	8.77
FEM	42.0	43.5	8.81
Difference (%)	23.1	2.8	0.5

5. CONCLUSIONS

A simple numerical approach for simulation of crack propagation in reinforced end-notched glulam beams was presented in this paper. The crack growth at the notch corner was modelled using the Cohesive Zone Modelling (CZM) in Abaqus. The effectiveness of the proposed model is verified by experiments, showing a fairly good agreement. The numerical modelling, as well as the experimental research, can help in better understanding of the crack initiation and crack growth phenomenon in reinforced end-notched timber beams. Initial cracking of the notch corner cannot be prevented by the reinforcement. However, by placing screws uncontrollable crack growth was limited and load-carrying capacity and deformability of beams were increased.

The presented models can be used for further parametric analyses, which would include varying the loading configuration, geometry and material properties. In addition, the model can be a good basis for further investigation of effectiveness of other types and positions of reinforcement like carbon or glass fibre-based polymer bars. Moreover, results obtained from FEM modelling can be useful in developing appropriate analytical design models for reinforced notched timber elements.

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