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Experimental and Numerical Analysis of Strengthening with Fibre Reinforced Polymers of Aged Timber Beams with Cracks and Knots

A. Lengyel and K. Saad

Department of Structural Mechanics
Budapest University of Technology and Economics, Hungary

Abstract

Performance of historical timber structures can be negatively affected by the changes in the material properties and the integrity of the elements over its service life. Preservation of degraded timber elements is preferable over replacement, which can often be performed economically by retrofitting using fibre-reinforced composites. However, the efficiency of reinforcement is heavily influenced by the actual conditions, like the presence of cracks and knots. To assess the mechanical behaviour of aged timber beams, an experimental programme and a numerical analysis were performed on sixty-years-old Norwegian spruce beams which contained several cracks and knots. Load-deflection curves and load-bearing capacity were determined by four-point bending tests. Detailed finite element models were constructed, accurately reproducing the actual geometric features of the beams. The experiments have shown that knots in the tension zone significantly reduce the bending capacity while composite reinforcement proved efficient in enhancing the mechanical behaviour regardless the presence of knots. Moment–deflection curve from the finite element modelling showed good agreement with the the experiments. The stress distribution in the model accurately predicted the point of failure initiation in the beam.

Keywords: timber, Norwegian spruce, aged wood, crack, knot, fibre reinforcement, bending test, finite element modelling

1 Introduction

Historical timber structures exposed to climatic changes are prone to suffer increasing damage and material degradation over time, including decay, geometric distortions, and cracking due to moisture content change. Therefore, restoration to extend their service life is a challenging task. Application of any technique, from the complete replacement of the damaged structural member to reinforcement with fibre composites or steel elements, requires the accurate assessment of the actual load-bearing capacity of the timber structural members. In this study, we investigate the bending moment capacity of aged spruce beams containing drying cracks and knots via testing and modelling.

Drying crack arise due to shrinkage anisotropy when the moisture content varies [1]. It is a typical problem in the case of historical buildings exposed to variable external conditions. Brol et al [2] performed bending tests on 130-years-old spruce beams observing that most specimens had some biological or mechanical degradation, and had longitudinal straight or sloping cracks. Mergny et al [3] presented a classification of crack types based on a sample of deeply cracked oak beams. Testing and modelling showed that cracks typically have moderate effect on the stiffness reduction (approx. 10%), though for long through cracks, the reduction can be as high as 25%. The authors also noted that it was impossible to identify the external crack which is responsible for the loss of stiffness.

While several authors address the problems related to glued laminated timber structures, e.g. [4, 5], few can be found on the modelling of sawn timber. Kovacikova et al [6] performed finite element analysis on glued laminated and sawn timber beams to determine the influence of flaws on the bending capacity, however, only short cracks or other imperfections were considered. The authors noted that flaws had worse negative effect on sawn timber than on glued laminated beams.

Knots are natural flaws in timber. While graded fresh sawn timber can be preselected for actual design requirements, flaws in aged wood from historical buildings must be considered as given conditions, and modelled accordingly. Knots have a negative effect on stiffness and load-bearing [7]. Particularly, strong fibre deviations in the vicinity of knots cause stress concentrations, which lead to tensile failure [8]. A parametric numerical study confirmed the decrease of capacity if the knot is located near the tensile edge [9].

In the lack of adequate and accurate analysis of naturally evolved cracks in timber, the aim of this study is to determine the effect of knots and severe longitudinal cracks on the bending capacity of aged timber beams. To achieve this goal, bending test were performed on four Norwegian spruce beams obtained from the reconstruction of a historical roof structure. Detailed finite element models were created to accurately reproduce the actual geometric features of each beam individually, including the cracks and the knots.

The layout of the remainder of this paper is as follows. Section 2 presents the test material and the bending tests. Section 3 elaborates the finite element model. Section

Specimen no.	Cross-section		Span [mm]	Knot position	Reinforcement
	width [mm]	height [mm]			
R1	112	70	1060	inside	yes
R2	104	84	1060	near edge	yes
U1	110	70	1060	near edge	no
U2	110	78	1000	inside	no

Table 1: Test specimen data.

4 presents the results of the experimental and numerical analyses followed by concise conclusions.

2 Experiments

During an extensive restoration programme involving Buda Castle in Budapest, Hungary, sixty-years-old spruce beams were removed from an historical roof structure. Although the structural elements were considered inadequate for further service and hence were replaced, they were offered for scientific analysis. We performed tests to assess the actual mechanical behaviour and investigate potential reinforcements. All beams had knots, longitudinal cracks of various lengths and depths, and most of them had some degree of damage. Small-scale specimens for compression tests had been cut from some of the beams in a previous research [10], while in this study, we tested the remaining four beams for bending. We retrofitted two of the beams with carbon-fibre reinforced plastic (CFRP) to determine the efficiency of reinforcement. In each case, a unidirectional 0.129 mm-thick ply was attached at full width and length to the bottom (tensile) face of the beam with epoxy, which formed the bond to the wood and embedded the carbon fibres simultaneously.

The four-point bending tests were performed by a standard MTS device with displacement control. The force exerted by the actuator was transmitted to the beam via a loading bridge with 0.30 m span, while the clear span of the beams varied between 1.00 m and 1.06 m. Displacement and force data were digitally recorded during the tests. Specimen data are summarized in Table 1 and the test arrangement is shown in Figure 1. Diagrams for the maximum bending moments against deflections are plotted in Figure 2.

3 Finite element modelling

Wood has natural flaws like knots and cracks, which can have a substantial effect on the load-bearing capacity and the failure mode of timber beams. In order to accurately

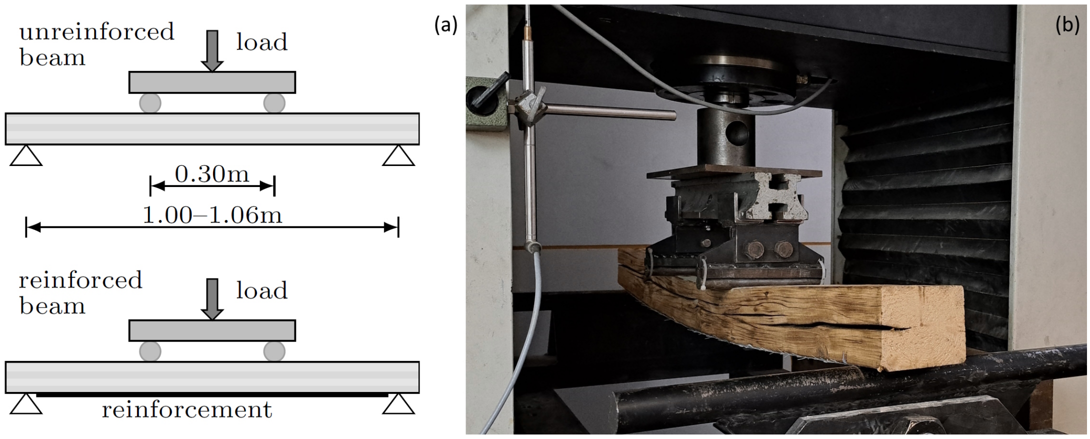

Figure 1: Four-point bending test; (a) Test arrangement; (b) One specimen under testing. Photo by the authors.

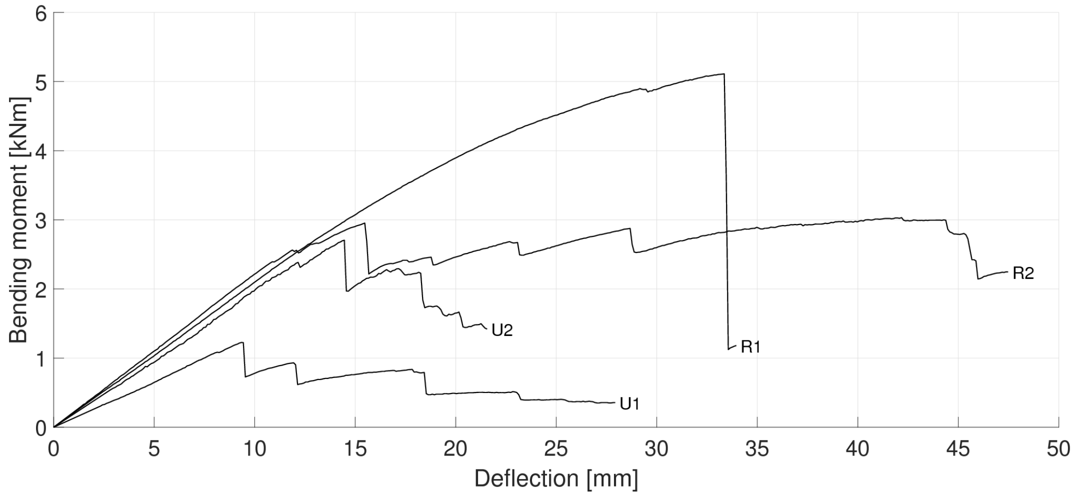

Figure 2: Mid-span bending moments against deflection for all beams.

model the cracks, knots, and related fibre deviations in both the unreinforced (without CFRP) and reinforced (with CFRP) rectangular timber beams, a three-dimensional finite element model was created using the general-purpose finite element modelling program ANSYS. Numerical simulations were performed to analyse the mechanical behaviour and predict the load-deflection curves from four-point bending. This section expounds the development of the three-dimensional FE model capable of capturing complex material behaviour and geometric irregularities in the investigated timber beams.

3.1 Geometry

Since failure typically starts at the weak spots in wood, such as knots and cracks, it is imperative to appropriately describe these weak places in the computational model and to generate an accurate representation of the imperfections.

In all beams under investigation, excessive cracks have formed over time. Each crack had its own geometric properties, which were measured and incorporated in the model in the geometry creation stage. It involved the identification of a sufficient number of data points (typically 5 to 10, depending on the length and shape) to accurately replicate the crack profile with position and slope with respect to the beam axis, as well as the width and depth of the crack. A parametric formulation was used in the ANSYS Parametric Design Language (APDL) to efficiently implement the formulation for all existing cracks. A precise geometric modelling of fibre deviations in the vicinity of knots is necessary, which was also performed in the geometry stage, using a similar parametric formulation. The CFRP sheet was modelled as a layer merged to the bottom face of the beam. A selected beam containing deep cracks and a knot (R1) is shown in Figure 3(a) and its finite element mesh in Figure 3(b). Figure 3(c) shows a detail of the fibre-reinforcement.

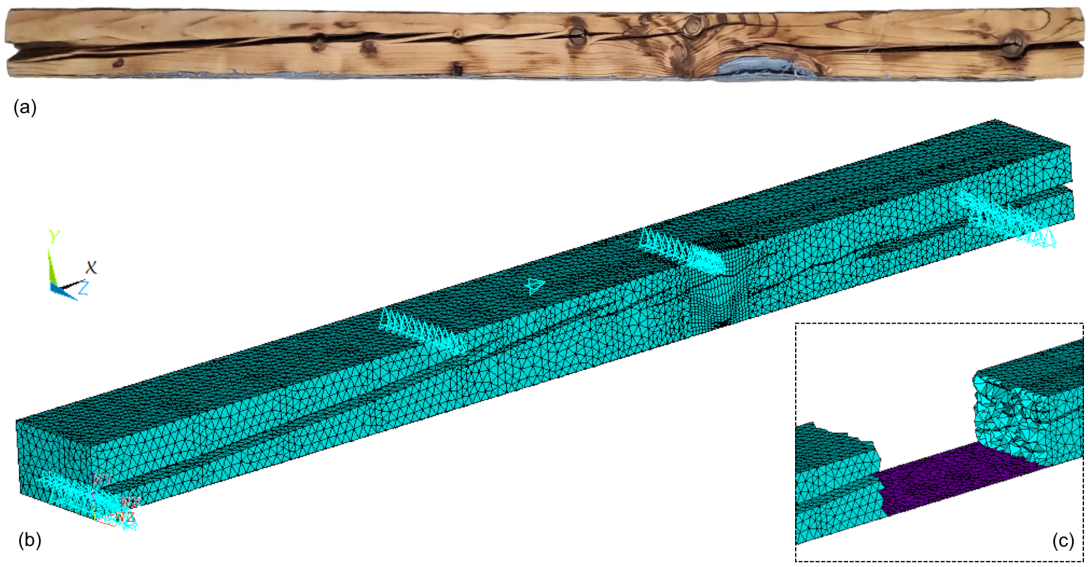

Figure 3: (a) Beam specimen R1, (b) the finite element model of the entire beam, and (c) a detail showing the fibre-reinforcement. Photo by the authors.

Boundary conditions were set to ensure simple supports, see the light blue marks in Figure 3(b). Vertical and transverse horizontal degrees of freedom were constrained at the supports, while a longitudinal constraint was defined at a point on the top at midspan to prevent longitudinal rolling. The displacement-controlled loading process was recreated by applying appropriate vertical constraints at the load locations with predefined vertical displacements in several steps.

3.2 Element types and materials

Given that wood exhibits both linear elastic and nonlinear inelastic behaviour under compression and linear elastic and quasi-rigid behaviour in tension, the Hill anisotropic material model was selected to describe the three-dimensional nonlinear behaviour, combined with the solid element SOLID45. The standard eight-node cubic type was applied in the vicinity of the knot whereas the tetrahedral option was used elsewhere to account for the complex geometry caused by sloping cracks. For every affected finite element in the vicinity of knots, element orientation was set appropriately to construct an accurate three-dimensional fibre representation and account for the diving angle of the knot. The CFRP sheet was modelled with linear transversely isotropic material and with element SHELL181, a finite element type suitable for analysing thin to moderately-thick shell structures, characterized by four-node elements featuring translational degrees of freedom exclusively at each node, with the membrane option utilized. The element requires to define several parameters for the composite, such as layer thickness, material composition, and orientation.

Most of the linear orthotropic properties of wood were adopted from literature [11]. In the case of bending, the behaviour of timber beams is primarily determined by the modulus of elasticity in the fibre direction in the linear range of deformations, while the others have little effect. When the stresses in the compression zone of the beam exceed the plastic compression strength, the response becomes nonlinear. Therefore, these two values were inversely identified using the experimental load-deflection curves. Table 2 summarizes the material properties used in the analysis. The fibre reinforcement is considered as a transversely isotropic material with the moduli of elasticity in the fibre and transverse directions equal to those of the fibres and the epoxy, respectively, obtained from the manufacturer. The stiffness of the reinforcement is predominantly determined by the modulus of the fibre.

Property	Wood	CFRP	Property	Wood	CFRP	Property	Wood	CFRP
E_x	6.60	234.00	G_{xy}	0.58	2.00	ν_{xy}	0.39	0.30
E_y	0.64	10.00	G_{yz}	0.03	3.84	ν_{yz}	0.49	0.30
E_z	0.42	10.00	G_{xz}	0.59	2.00	ν_{xz}	0.03	0.30

Table 2: Elastic material properties for wood and reinforcement. Elastic moduli E_i and shear moduli G_{ij} are given in units of GPa. Poisson's ratios ν_{ij} are scalars.

3.3 Failure

In the presence of knots, failure in wood is typically initiated in the vicinity of knots due to strong deviations of fibre directions from the reference longitudinal direction.

Additionally, in the presence of large cracks, a considerably more complex behaviour may be experienced both in terms of geometry and stress distribution. In the first stage of the modelling, only beam R1 is considered, whose failure was not significantly affected by the cracks (see Section Results for details). The modelling aims to inversely determine the two major parameters of timber, the longitudinal modulus and the compression yield stress, and to validate the model via comparison of the measured and the simulated load–deflection curves, as well as the comparison of the simulated stress distribution and the observed failure mode.

4 Results

4.1 Load-bearing

Results of the four-point bending tests are summarized in Table 3. The bending moment capacity and the associated displacement is defined as the instant when the first significant drop of load takes place, even though the displacement controlled test could be continued. All beams had unique geometries because the knot and crack patterns have to be considered as given, unlike fresh sawn timber, which can be pre-selected for design appropriately. Beams R2 and U1 contained knots in the tensile zone near the edge in the middle segment of the beams, where the maximum bending moments arise. Beams R1 and U2 also had knots in the middle segment but they were closer to the neutral axis. Comparing the two unreinforced beams (U1, U2), it is found that the presence of an edge knot significantly reduced the moment capacity (-50.8%). Likewise, comparing the reinforced beams (R1, R2), the effect of the edge knot was apparent in the reduction of the capacity (-30.6%). This finding conforms with the results of our previous parametric finite element simulations of unreinforced timber beams, showing that the capacity reduction increases monotonically with the knot's distance from the neutral axis [9].

Specimen no.	Capacity at first significant damage		Knot position
	moment [kNm]	deflection [mm]	
R1	5.395	33.36	inside
R2	3.741	15.48	near edge
U1	1.552	9.34	near edge
U2	3.156	14.46	inside

Table 3: Test specimen data.

Comparing beams with edge knots (U1, R2), it is found that the reinforcement can significantly increase the capacity ($+141.0\%$). In the case of beams with knots far from the tensile edge (U2, R1), the improvement is also large ($+70.9\%$). Note that the specimen dimensions are not identical: beam R2 is slightly more robust than the others. Thus, an equivalent cross-section would result in a somewhat lower moment capacity, which in turn would increase the difference between R1 and R2, and also mitigate the extreme difference between U1 and R2. However, even though only four specimens could be acquired for testing, the differences are significant.

In the CFRP sheet, the contribution of the epoxy to the mechanical behaviour is negligible, whereas the thin ($0.15\% - 0.18\%$ cross-section area ratio) carbon fibre ply is responsible for the improvement. This improvement is higher than or similar to the typical values obtained from measurements on old timber beams, e.g. an increase of up to 88% achieved by 0.5%–0.6% reinforcement ratio [12] or an increase of 60% achieved by 0.123% ratio [13]. The results indicate that the CFRP can effectively compensate for the loss of cross-sectional integrity caused by the cracks.

4.2 Failure

The unreinforced beam U1 with a knot at the tension edge suffered a brittle failure. The load–deflection curve was linear up to rupture at a knot. Further increasing the displacement, the associated load started to rise again, at a gentler slope up to another drop, followed by a few similar cycles. During the process, the local peaks and the subsequent slopes decreased, indicating that the damaged region gradually propagated. Under natural conditions, this phenomenon could not have been observed; in fact, in the case of a force-controlled loading, the beam would have experienced a rapid progressive failure and a total collapse at the first rupture. The ruptured section is shown in Figure 4.

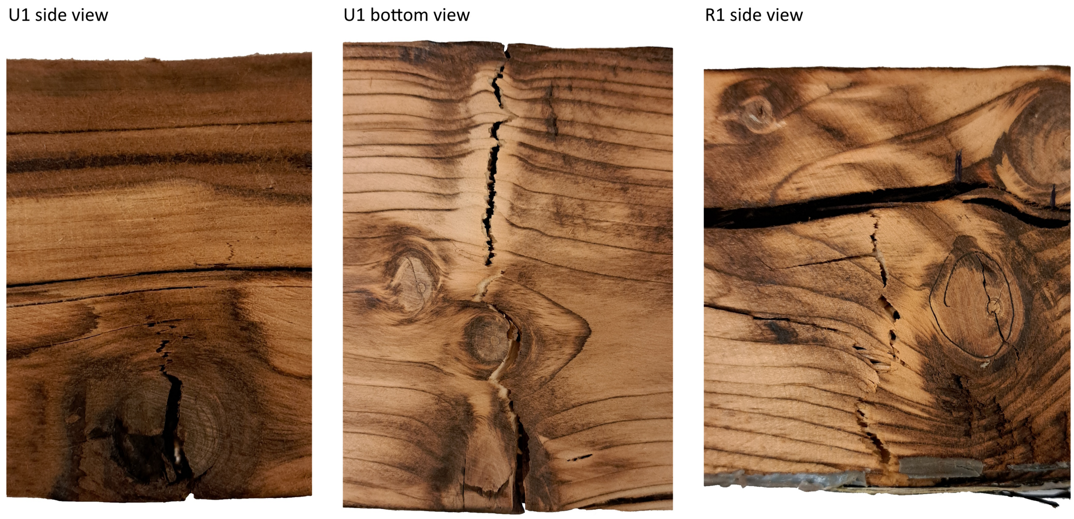

Figure 4: Failure of selected beams. Photos by the authors.

The unreinforced beam U2 showed similar load–deflection characteristics. The failure was initiated in the vicinity of a knot. Since the knot was located inside the beam in the middle segment, it had less effect on the load-bearing. Progressive failure was again prevented by the displacement control.

The reinforced beam R1 exhibited a robust performance with linear elastic initial behaviour and gradually increasing ductility in the compression zone in the subsequent phase of the loading process. A small drop at high load level indicated a localised damage in the timber, followed by further increase of the load. Failure occurred at the rupture of the CFRP sheet, which led to a rapid total collapse. This beam had no knot near the tensile edge, and the reinforcement could effectively form a composite structure with the timber to reach a high load-bearing capacity. The load–deflection curve revealed that the geometric features (cracks and knots) had little effect up to near the failure. The ruptured section is shown in Figure 4.

Beam R2 had an edge knot, which initiated an early failure. However, during further repeated phases of loading and localised damages, the load gradually rose to a level similar to the one prior to the first significant damage. It indicates that the fibre reinforcement could maintain the integrity of the beam during large displacements.

In the case of one beam (R1), local damages had insignificant effect on the mechanical behaviour, whereas the other three require additional detailed stress and failure analysis in connection with the actual knot and crack patterns.

4.3 Finite element modelling

The model geometry of beam R1 is shown in Figure 3. The wood modulus of elasticity in fibre direction and the compression yield stress were inversely identified by comparison of the measured and the simulated moment–deflection curves. The simulation accurately reproduced the measurements by setting $E_x = 6.60$ GPa and $f_{cy} = 32$ MPa, see Figure 5. The modelling agreed well with both the linear slope of the elastic range and the curvature of the nonlinear ductile behaviour. A small local damage in the wood prior to ultimate collapse was not captured, as it would require a detailed failure analysis, which is beyond the scope of this work.

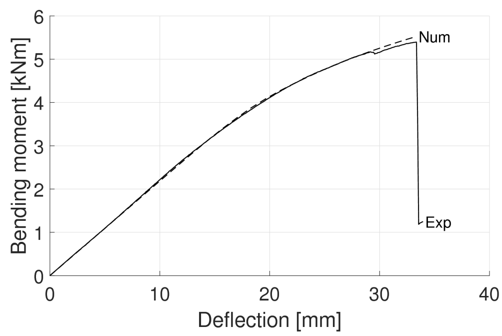

Figure 5: Experimentally and numerically determined moment–deflection curves for beam R1.

The stress analysis confirmed that the vicinity of a knot in the tension zone near one of the loading points was responsible for the actual observed failure, see Figure 6. High normal stresses in the longitudinal direction are found in the extreme tensile fibres in the middle segment of the beam with maximal values reached in the vicinity of a knot. The von Mises stresses further display the stress concentration around the knot. The Tsai–Wu failure strength ratio index identifies the weak location where the failure is expected to initiate. The diagram of the shear stresses in the vertical plane show above-the-average values near the knot and the lines of the cracks. Although cracks did not play a readily identifiable role in the failure of this beam, the modelling of the rest of the beams in the continuation of the research is going to incorporate the detailed failure analysis.

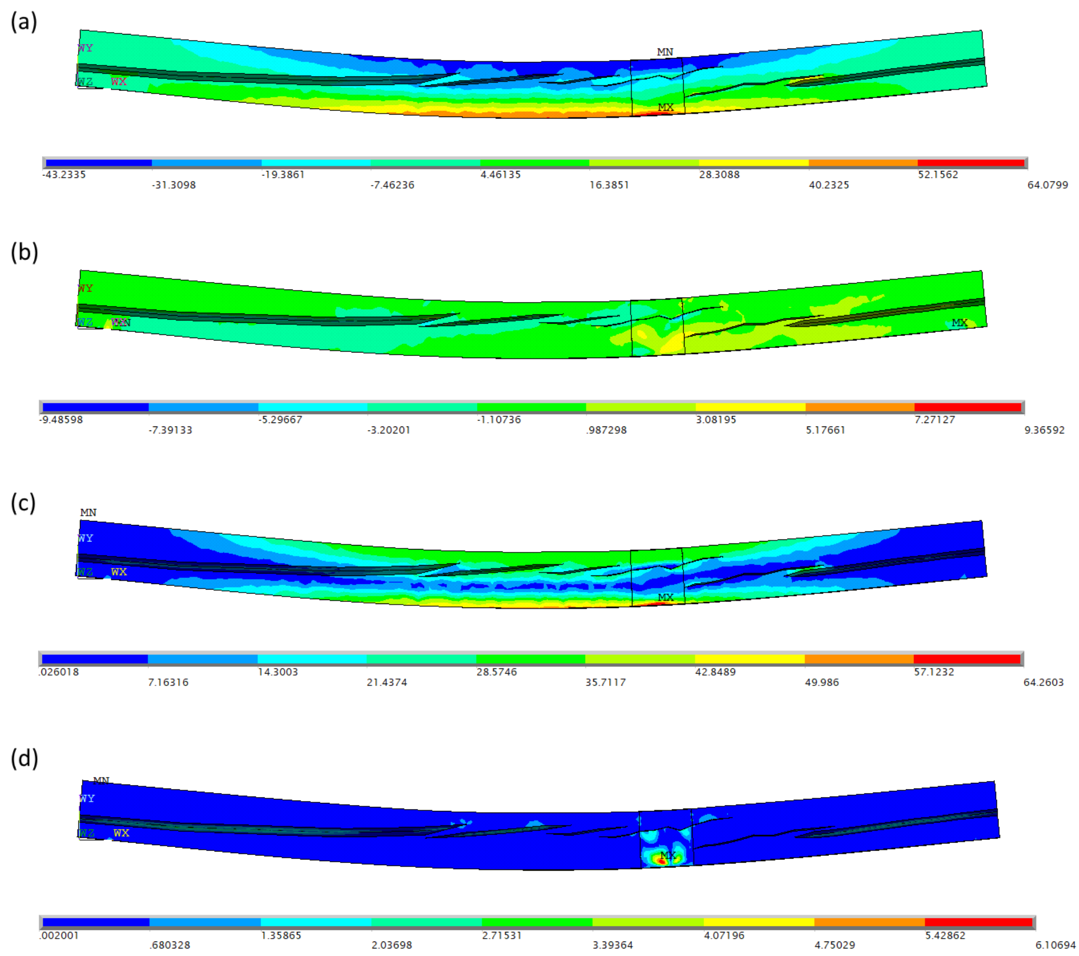

Figure 6: Stress distribution in wood in beam R1: (a) longitudinal normal stresses, (b) shear stresses in the vertical plane, (c) von Mises stresses, (d) Tsai–Wu failure strength ratio index.

5 Concluding remarks

In this study, we have performed experimental and numerical analysis on aged Norwegian spruce beams to determine the effect of knots and excessive naturally evolved cracks on the mechanical response and the load-bearing capacity. Two beams were kept intact as a reference while two others were retrofitted with carbon-fibre reinforced polymer sheets on the tension side to enhance the load-bearing capacity. Load–deflection curves were determined from four-point bending tests. A detailed finite element model was illustrated for a selected beam to accurately replicate the actual knots, cracks, and fibre pattern in the timber. The main findings of the investigations are as follows:

- The experiments have demonstrated that knots located in the high moment segment near the tensile face significantly reduced the bending moment capacity both in the case of reinforced and unreinforced beams.
- The experiments have also shown that reinforcement could significantly boost the load-bearing by compensating for the loss of cross-sectional integrity and restoring tensile capacity both in the cases of knots located near the tensile edge or the neutral axis. The capacity increase exceeds the typical performance of reinforcement applied to solid sawn timber, indicating that excessive cracks have considerable effect on the load-bearing without reinforcement.
- Knotted sections, especially in the case of knots near the edges are prone to initiate failure. Therefore, applying additional reinforcement is advisable to strengthen these areas and maintain the overall integrity of the structure.
- The finite element analysis of a beam which did not exhibit multiple local damages during loading has revealed that the stress concentration in the vicinity of a knot led to the failure of the beam.

The continuation of the current work aims to extend the finite element modelling with the analysis of the failure mechanism in association with the intricate crack patterns.

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