



FINITE ELEMENT MODELLING OF THE RESTORATION OF WOODEN STRUCTURAL ELEMENTS WITH 3PHV60 TYPE EPOXY RESIN

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Abstract

This article deals with the issue of repairing wooden structural elements with 3PHV60 type epoxy resin. The primary objective of this paper is to model the effects of cracking. Finite element design software has been used to study this issue and the results obtained have been compared with the results of previously performed destructive tests. The results of the damaged specimens were compared with the results of the resin-restored specimens.

Keywords: *finite element modelling, structural timber, timber repair, epoxy resin, consolidation.*

1. Introduction

Nowadays, the rehabilitation of buildings is becoming increasingly important, but the restoration of damaged structural elements of a building poses many challenges. Structural restoration requires a responsible engineering approach, including an economical and environmentally conscious approach. One of the main principles of an economic and environmental approach is restoration/intervention according to the extent of the damage.

The aim of this multi-stage research is to investigate the local restoration of locally damaged timber structural elements with 3PHV60 type epoxy resin. The main question of the research is whether resin can increase the load-bearing capacity and stiffness of damaged timber structural elements.

2. Initial situation

The first step of the research was to investigate the mechanical properties of the 3PHV60 resin for the restoration of wooden structural frames, which is the subject of a previously published article - *Determination and comparison of the me-*

chanical properties of epoxy resin type 3PHV60 with C24 structural graded softwood. [1] To investigate the mechanical properties of the 3PHV60 type epoxy resin used, studies based on fracture tests were carried out. We have supplemented our knowledge with information provided by the manufacturer. After studying the mechanical properties of the resin, the applicability of the resin on wood was investigated. For more information on this issue, see the study entitled *Application of 3PHV60 type epoxy resin for the repair of timber structures.* [2]

3. Presentation of the test specimens

The study investigates the effect of cracks in the wooden structural members. To calculate the shear stresses of the elements subjected to bending, Eurocode 5 uses a k_{cr} coefficient (crack for shear resistance) which takes into account the effect of cracking to calculate the effective section width.

When determining the shear capacity, the element width to be taken into account is calculated by the relation $b_{ef} = k_{cr} \cdot b$. For sawn and glued laminated timber, the value of k_{cr} is 0.67. Based on this value, weakening with a regular geome-

try was applied to 1/3 of the tested cross-section along the entire length of the specimen.

As a starting point, undamaged specimens were tested. Afterwards, we continued with the testing of unilaterally weakened specimens and finally specimens repaired with resin. The results of the tested cases were compared.

For the destructive tests and finite element models, the static model illustrated in Figures 2–4. was used, taking into account the requirements of the standard MSZ EN 408:2010+A1:2012 [3].

During the destructive tests, the vertical displacement was measured at midspan and the force F at the moment of fracture. The study entitled *A The Use of Epoxy Resin in the Repair of Cracked Wooden Structural Elements* [4] provides a detailed demonstration of the results of the destructive tests.

4. Finite element modelling

After destructive tests, the experiments were also modelled by finite element method using ANSYS 2024 R2 software, and the resulting force-displacement diagrams were compared with those obtained in non-destructive tests. For the nonlinear calculation, the wooden specimen was constructed from SOLID45 type elements, assuming a linearly elastic orthotropic material with a material model that is hardening in tension and perfectly ductile in compression. The resin reinforcement was modelled using SOLID185 element type and assuming a linearly elastic isotropic material.

Assuming perfect working together between the two materials, the displacements at the common nodes of the different elements are linked so that they are identical throughout the calculation. Articulated supports were defined at one end of the beam and roller supports at the other end. The loads were placed on the beam at the third points on 40x40 mm rigid load distribution plates with small displacement controlled loads. The elements are composed of 5 mmx5 mmx5 mm finite elements.

In the theoretical model, the elastic moduli, Poisson's ratios and limit stress values of the materials were taken into account based on the results of the destructive tests and data from the literature. The parameters of the wood material model are summarized in Table 1.

4.1. Intact wood specimens

The force-displacement diagrams obtained from the destructive tests of the undamaged specimens were constructed alongside the diagrams

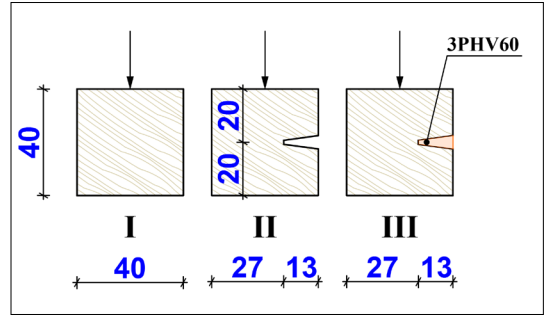


Fig. 1. Cross section of the test specimens examined.

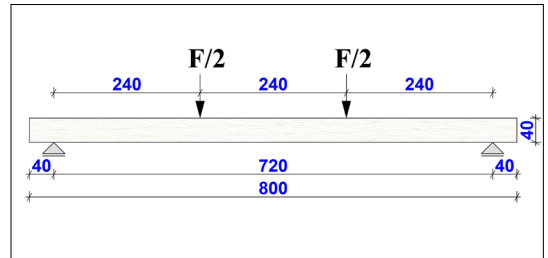


Fig. 2. Experimental configuration used for testing intact wood specimens.

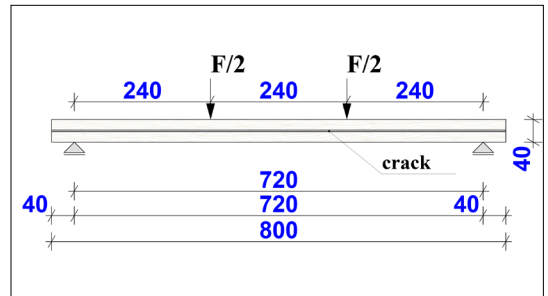


Fig. 3. Static model used for testing wooden specimens cracked on one side.

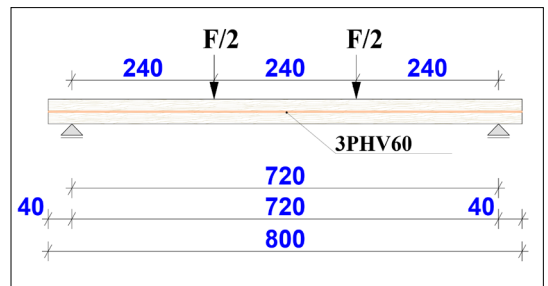


Fig. 4. Static model used in the testing of resin-restored wood specimens.

Table 1. Mechanical properties of wood used in finite element models

Mechanical property	Value
Young-modulus (x direction)	11000 N/mm ²
Young-modulus (y direction)	649 N/mm ²
Young-modulus (z direction)	1408 N/mm ²
Poisson's raio (xy direction)	0.462
Poisson's ratio (xy irány)	0.255
Poisson's ration (xz direction)	0.422
Shear modulus (xy)	1364 N/mm ²
Shear modulus (yz)	110 N/mm ²
Shear modulus (xz)	1320 N/mm ²
Yield stress (tension, x direction)	50 N/mm ²
Young-modulus after yield stress (tension, x direction)	500 N/mm ²
Yield stress (tension, y direction)	5 N/mm ²
Young-modulus after yield stress (tension, y direction)	100 N/mm ²
Yield stress (tension, z direction)	5 N/mm ²
Young-modulus after yield stress (tension, z direction)	100 N/mm ²
Yield stress (compression, x direction)	30 N/mm ²
Young-modulus after yield stress (compression, x direction)	0 N/mm ²
Yield stress (compression, y direction)	50 N/mm ²
Young-modulus after yield stress (compression, y direction)	0 N/mm ²
Yield stress (compression, z direction)	50 N/mm ²
Young-modulus after yield stress (compression, z direction)	0 N/mm ²

obtained in the finite element model, so that the correctness of the model could be checked **Figure 5** illustrates the destructive and finite element (ANSYS) force-displacement diagrams of undamaged specimens. The dashed line indicates the force-displacement function of the theoretical model. The vertical displacements measured in the theoretical model at the moment of failure are illustrated in **Figure 6**. **Figure 7** shows the evolution of the normal stresses and **Figure 8** the evolution of the shear stresses.

In the finite element model, the Young's modulus of the resin in all directions is 650 N/mm² and the Poisson's ratio is 0.3.

In the destructive test, the average of F breaking forces was 5569 N and the average of vertical displacements at mid-span was 28.26 mm. In the theoretical model, the breaking force was 5106 N and the vertical displacement at mid-span was 23.86 mm.

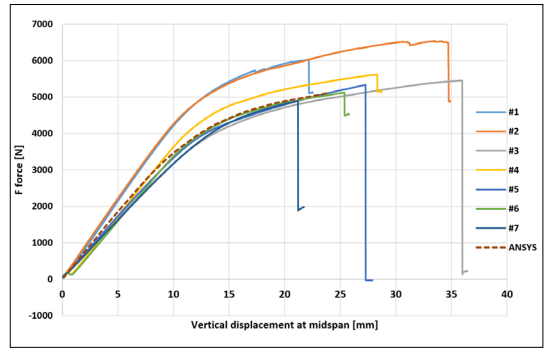


Fig. 5. Force-displacement diagram of undamaged test specimens.

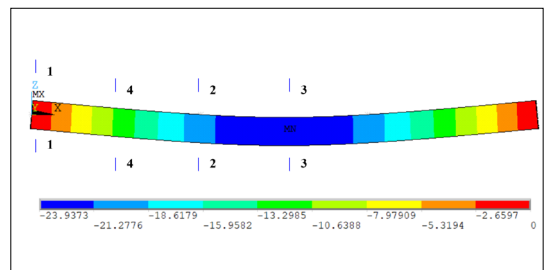


Fig. 6. Displacement diagram of undamaged specimens in ANSYS finite element software.

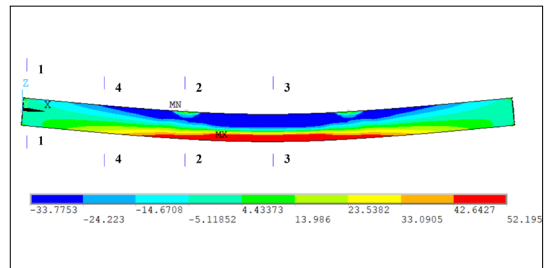


Fig. 7. Normal stress diagram of undamaged specimens in ANSYS finite element software.

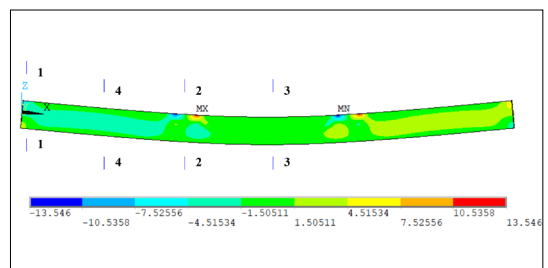


Fig. 8. Shear stress diagram of undamaged specimens in ANSYS finite element software

4.2. Test specimens cracked on one side

After destructive testing, a finite element method was also used to investigate an element with a simulated crack on one side of the element at the neutral axis. **Figure 9** shows the specimen meshed with the finite element software. **Figure 10** shows the force-displacement diagram of the finite element model and the force-displacement diagrams of the destructive test. **Figure 11** shows the vertical displacements of the cracked element in mm. **Figure 12** shows the distribution of normal stresses of the cracked element in N/mm^2 . **Figure 13** shows the shear stresses of the cracked element in N/mm^2 .

The force-displacement diagram of the element modelled with the finite element software matches well with the diagrams of the fractured specimens.

The average value of the breaking forces obtained in the destructive tests was 5363 N and the average value of the displacements measured at midspan was 29.33 mm. The breaking force obtained by the finite element method was 5018 N, with a displacement of 23.43 mm.

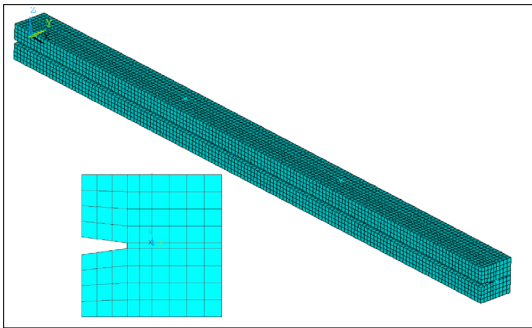


Fig. 9. Finite element model of a specimen cracked on one side.

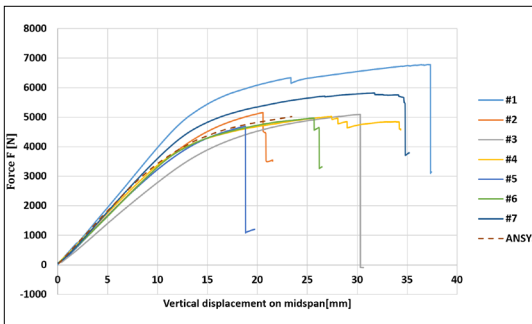


Fig. 10. Force-displacement diagrams of test specimens cracked on one side.

4.3. The resin-restored test specimens

Based on the geometry of the cracked specimens, the resin-restored elements were prepared. **Figure 14** summarizes the force-displacement diagrams of the destructive tests and the theoretical model. The force-displacement function of the finite element model is indicated by the dashed line.

For the repaired specimens, the mean value of the breaking forces obtained during the destructive tests was 5631 N and the mean value of the vertical displacements at midspan was 26.76 mm.

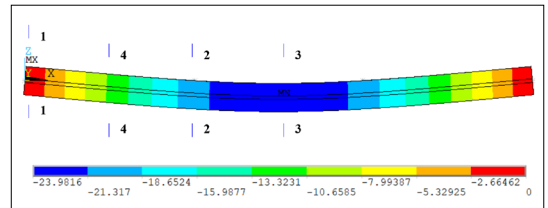


Fig. 11. Vertical displacements of the cracked element.

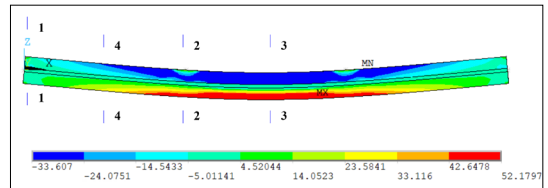


Fig. 12. Distribution of the normal stresses of the cracked element.

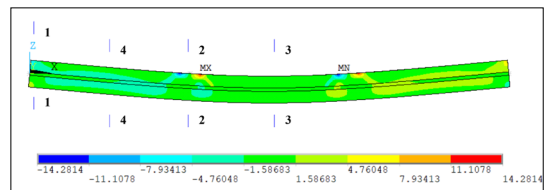


Fig. 13. Distribution of the shear stresses of the cracked element

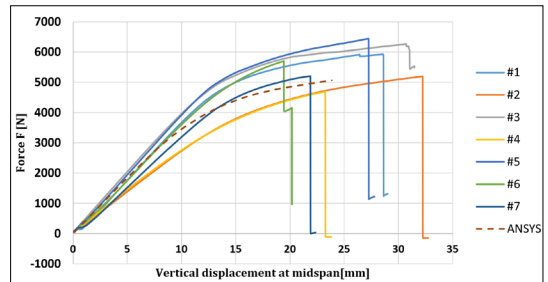


Fig. 14. The force-displacement diagram of the resin-restored test specimens.

In the theoretical model, the mean value of the breaking forces was 5065.64 N and the mean value of the vertical displacements at midspan was 23.86 mm. **Figure 15** shows the vertical displacements in mm of the resin-restored specimen.

Figure 16 illustrates the distribution of the normal stresses in N/mm^2 of the element restored with epoxy resin. **Figure 17** shows the distribution of the shear stresses in N/mm^2 of the resin-restored element.

4.4. Comparison of cracked and resin-repaired cases

The effect of the resin was analysed by comparing the normal and shear stress diagrams of the sections in the finite element models. Cross sections were taken at midspan (3-3) and 120 mm from the support (4-4). In the section 3-3 there is a maximum normal stress point and in the section 4-4 a maximum shear stress point (**Figures 18–27**). The cross-sections where stress maxima are found and local effects are not present were investigated. For the sections at the supports and at the force inputs, the stress distribution is not investigated at this time to avoid local effects.

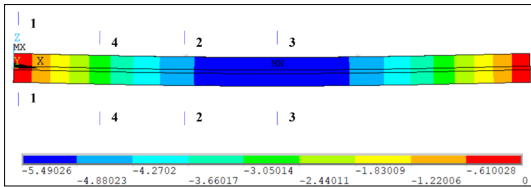


Fig. 15. Vertical displacements of the resin-restored element.

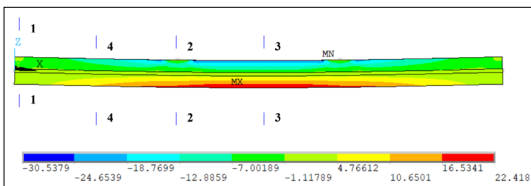


Fig. 16. Distribution of the normal stresses of the resin-restored element.

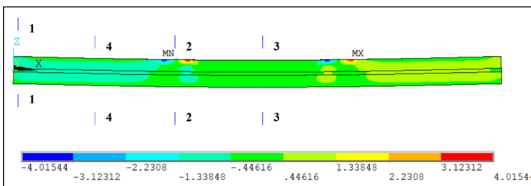


Fig. 17. Distribution of shear stresses in the resin-restored element.

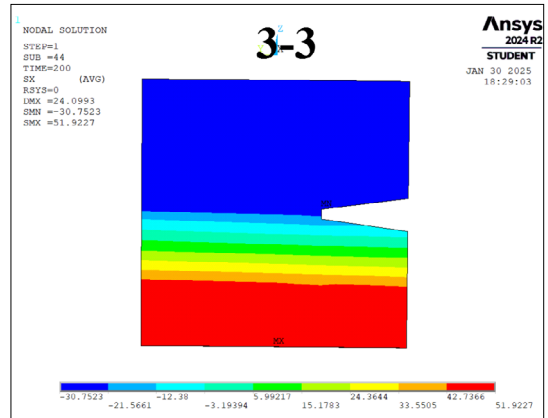


Fig. 18. Distribution of normal stresses in section 3-3 for the cracked element.

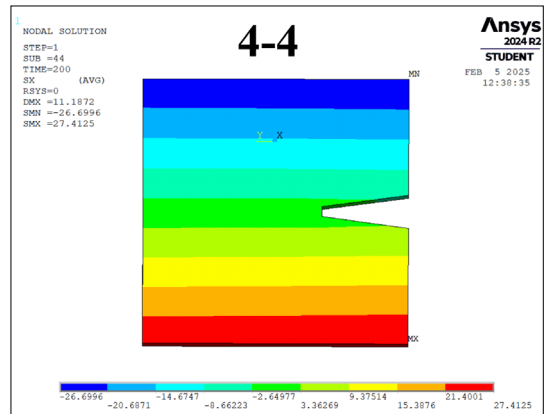


Fig. 19. Distribution of normal stresses in section 4-4 for the cracked element.

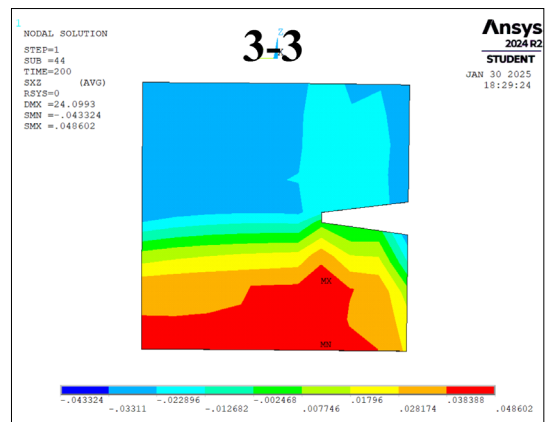


Fig. 20. Distribution of shear stresses in section 3-3 for the cracked element.

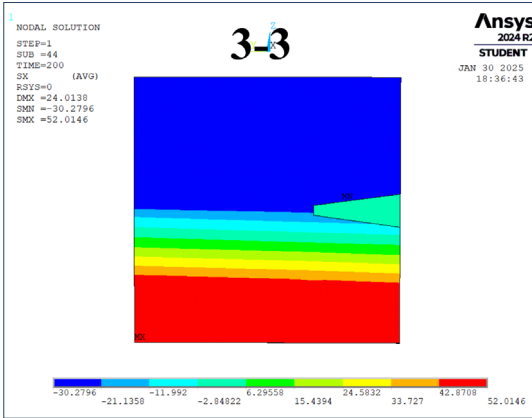


Fig. 21. Distribution of shear stresses in section 3-3 for the resin-restored element.

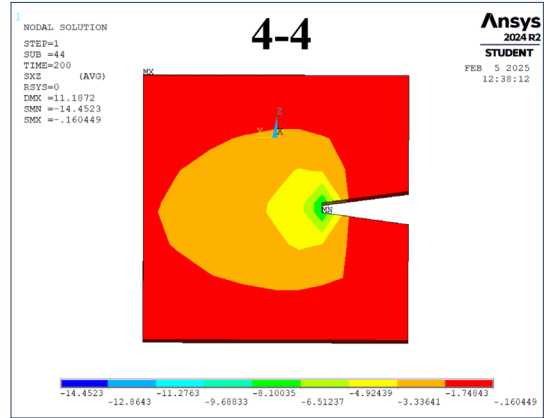


Fig. 24. Distribution of shear stresses in section 4-4 for the cracked element.

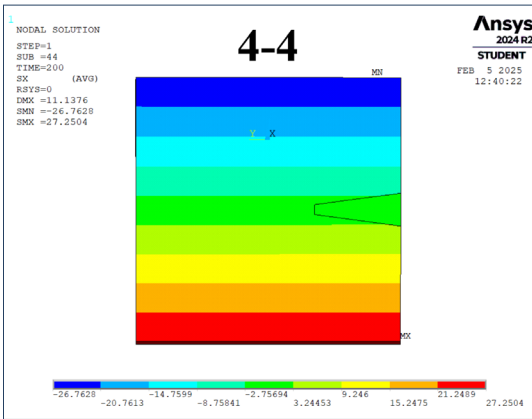


Fig. 22. Distribution of normal stresses in section 4-4 for the resin-restored element.

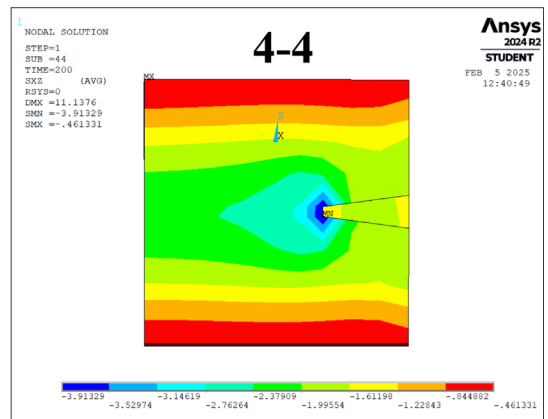


Fig. 25. Distribution of shear stresses in section 4-4 for the resin-restored element.

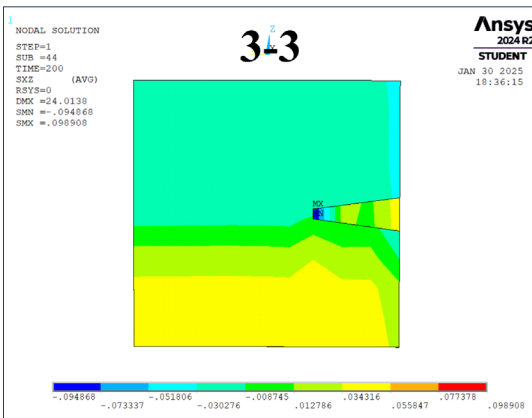


Fig. 23. Distribution of shear stresses in section 3-3 for the resin-restored element.

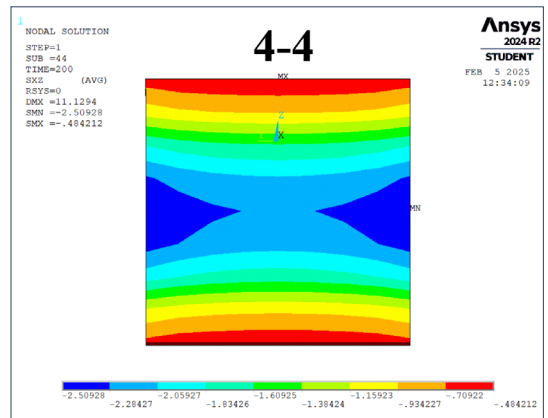


Fig. 26. Distribution of shear stresses in section 4-4 for the intact element.

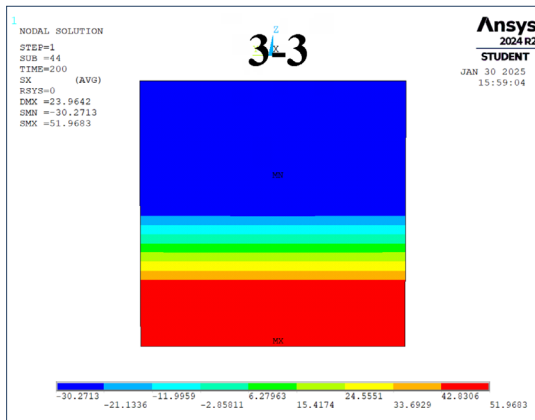


Fig. 27. Distribution of normal stresses in section 3-3 for the intact element.

5. Conclusions

The effect of cracking is not significant for the distribution of normal stresses in either case. This phenomenon can be explained by the position of the crack in the cross section of the element (at the neutral axis). For this reason, the fracture forces do not differ greatly. Fracture occurs due to the exceeding of the limit stress of the normal stresses at this crack depth and position.

Cracking plays a key role in the development of shear stresses. The crack is located at the maximum of the expected shear stress. Figure 18 illustrates the distribution of shear stresses of intact specimens, where the shear stress XZ peaks at the centre of the cross-section, as expected.

Figure 16 illustrates the shear stress diagram of the cracked specimen in cross section 4-4. In the vicinity of the crack, a stress peak is observed with a peak stress value of 8 N/mm², which is more than three times higher than the corresponding point on the intact specimen.

In Figure 17 for the resin-restored specimen, the application of resin has a positive effect on the shear stress evolution. The stress peak is found at the peak of the restored crack, but its value is more than 2 times smaller than for the cracked

element. By using the epoxy resin, we realized to reduce the stress peaks and to obtain values close to the intact cross-section in terms of shear stress evolution.

In the next steps of the research, we aim to investigate the effect of cracks on both sides of the cross-section and their repair with resin. Subsequently, we also want to investigate cases where the position of the weakening may influence the evolution of the normal stress.

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