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A FRACTURE MECHANICAL AND ANISOTROPIC FEM MODEL OF THE "RECONWOOD JOINT" AND EXPERIMENTAL VERIFICATION

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ABSTRACT: Contemporary capabilities in timber fabrication have encouraged the advancement of robotic manufacturing and assembly. In this paper, the *ReconWood joint*, a new type of reversible joint conceived for robotic timber assembly is investigated. The joint use CNC milled shear-keys to ensure enhanced shear capacity and more ductile behaviour over the conventional dowel-type connection. More specifically, we here establish a method for the modelling and structural analysis of such joint where the complex nature of timber is tackled by using material laws which are readily available in most commercial FE software. The paper presents a hybrid material model using the Hill Criterion in combination with fracture mechanics (CZM) to appropriately describe these behaviours. The material model is implemented in a three-dimensional FEM model to simulate the joint's mechanical behaviour, and a test series is presented to validate the modelling approach. The results show that the model is able to predict the mechanical response with great precision, both in relation to the stiffness, ultimate strength, and failure mode.

KEYWORDS: Timber joint, Solid 3D FEM, Experiments, Fracture mechanics, Anisotropy

1 INTRODUCTION

Timber is considered one of the most promising construction materials of the future due to its carbon sequestration capability, its relatively rapid circles of regrowth, and its re-use and adaptation potential while offering great mechanical performance and lightweightness [1].

The structural capacity of timber structures is often governed by the load-carrying capacity or deformations of the bolted joints. However, the past decade's development of contemporary fabrication technologies within timber engineering has led to the advancement of novel, refined, joint typologies. This paper presents a second generation of a shear-key-based bolted joint [2], specifically the *ReconWood joint,* a part of the *ReconWood construction system*. The construction system has been developed by the CREATE Group at the University of Southern Denmark (SDU CREATE), envisioning building components that are robotically assembled, dis-assembled and re-assembled, can be reconfigured into various structural and functional formations and are structurally optimised for re-use [3-5].

The *ReconWood joint* improves the stiffness and load-carrying capacity over conventional bolted joints [2]. To ensure its reusability within multiple structural configurations over time and provide a viable design and engineering tool for the reconfigurable wood architecture of the future, a reliable structural model that encompasses the complex nature of timber's strength and stiffness is crucial. As the capacity and stiffness of the joint are governed by very complex mechanisms and nonlinear material properties, a reliable model must be based on the finite element method, FEM. This paper aims to showcase a reliable model for structural analysis of the *ReconWood joint* using widely available commercial FEM software and perform an experimental verification.

This paper first introduces the *ReconWood joint* before presenting a detailed description of an appropriate material model for structural analysis of the joint. Hereafter, a *ReconWood joint* is analysed, first via FEM and afterwards experimentally. The results are compared before the paper rounds off with a conclusion.

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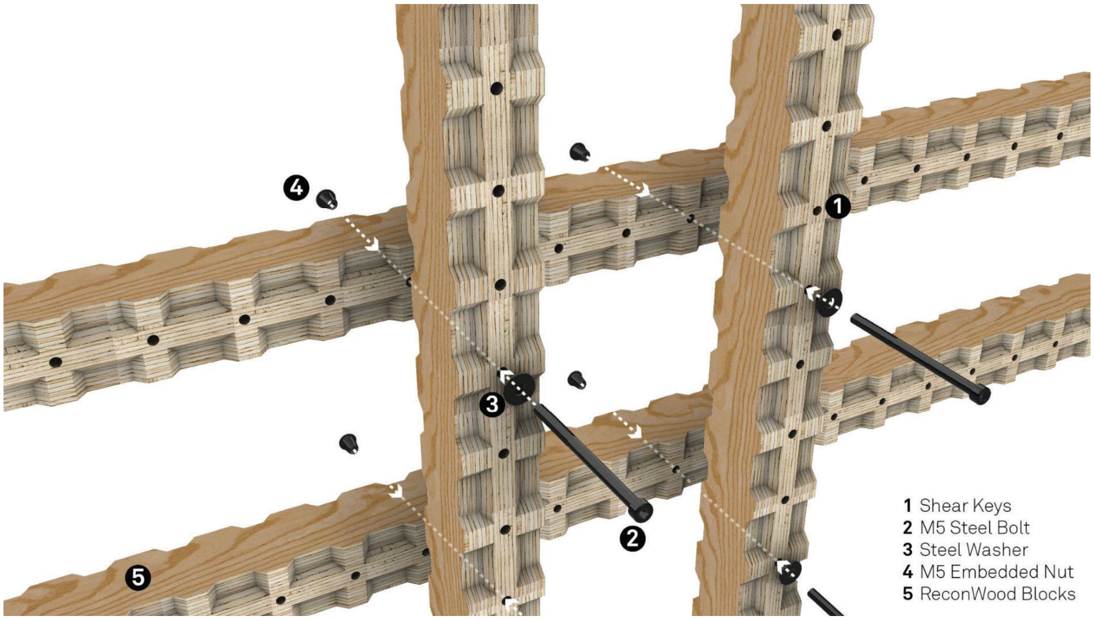

Figure 2: *Exploded view of the ReconWood joints and the construction system*

2 THE *RECONWOOD JOINT*

The *ReconWood joint* is a part of the *ReconWood construction system* [3,4] conceived as a reusable and reconfigurable construction kit made out of discrete building blocks with reversible joints. The blocks and the joints are designed to facilitate robotic assembly and re-assembly of various structural formations as seen in Figure 1. [5]

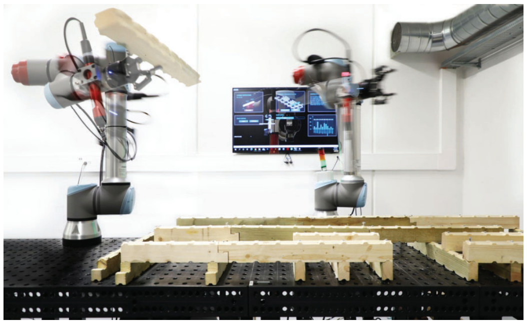

Figure 1: *Collaborative robot assembly of a ReconWood construction system*

The *ReconWood joints* are characterised by robotically milled cross-shaped male/female interlocking features, connected by a steel bolt with insert nut fasteners (Figure 2). The interlocking three-dimensional geometry of the joints assures precision and rigidity during the assembly process.

In the assembled structure, these joints ensure an increased stiffness and capacity when subjected to shear due to the shear key effect facilitated by the milled features [2], instead of activating dowel and rope actions as for the conventional bolted joints. The increased capacity results in a one-bolt joint which (*i*) eases the robotic assembly, and (*ii*) the edge distance does not govern the block dimensions. The increased stiffness of the joints is highly beneficial for the *ReconWood construction system* due to the large number of connections within such a structure, where the global stiffness is significantly affected by the joint stiffness.

3 MATERIAL MODEL FOR NUMERICAL ANALYSIS

The aim of the FEM model is to evaluate the stiffness, load-carrying capacity, and reusability of the *ReconWood joint*. To establish this, the material model must account for the complex mechanisms and nonlinear material properties of timber.

3.1 TIMBER'S MECHANICAL PROPERTIES

Timber is a complex anisotropic material due to its structure. Comprised of tube-shaped cells in a lignin matrix, the strength, stiffness, and post-peak behaviour of timber depend on the direction and the type of stress applied. [6]

The anisotropy of timber is often defined by a cylindrical coordinate system with three axes denoted longitudinal (L), radial (R), and tangential (T), see Figure 3. A common practice in timber engineering is a simplification of using the same mechanical properties for radial and tangential direction resulting in two distinctive directions: parallel-to and perpendicular-to the grain direction. [7,8]

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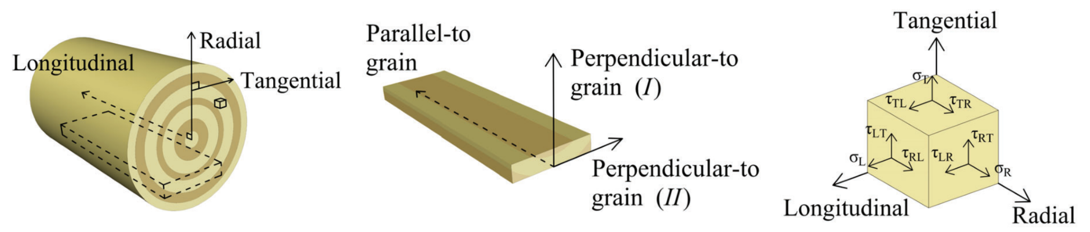

(i) *(ii)* *(iii)*

Figure 3: *Material directions of timber and 3D stress components.*

Typically, timber's properties are described for compression, tension, and shear, individually. When subjected to tension, timber can be described by linear elastic and brittle behaviour regardless of the grain orientation. However, the stiffness and strength are highly anisotropic parallel to the grain. In compression, timber has ductile behaviour with anisotropic post-peak behaviour in all directions. Compression parallel to grain direction is characterised by strain softening, while compression perpendicular to grain direction shows strain hardening. [6]

The six shear stress components, referring to the cylindric coordinate system (see Figure 3) are due to equilibrium pairwise equal ($\tau_{\mathrm{TL}} = \tau_{\mathrm{LT}}, \tau_{\mathrm{RL}} = \tau_{\mathrm{LR}}, \tau_{\mathrm{RT}} = \tau_{\mathrm{TR}}$). Each of the three pairs of stress components has an individual shear strength. The shear strength for the four parallel-to stress components ($\tau_{\mathrm{TL}}, \tau_{\mathrm{LT}}, \tau_{\mathrm{RL}}, \tau_{\mathrm{LR}}$) are almost identical and due to convenience, the lowest strength τ_{TL} is used. However, the strength for the perpendicular-to shear stress components, also known as rolling shear, is significantly lower[6,7]. The application of this is further discussed in Section 4.4.

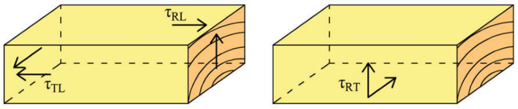

Figure 4: *Shear directions in timber*

This paper proposes a hybrid modelling approach as no available model exists that *(i)* addresses the anisotropic strength and stiffness of timber in combination with simultaneous brittle and ductile behaviour, and *(ii)* is readily implementable in commercial software. Therefore, the material model presented is divided in two - one for the brittle behaviour and one for the ductile behaviour.

3.2 MODELLING THE BRITTLE BEHAVIOUR

For the modelling of brittle failure within solid wood, three main approaches are found in the literature: *Cohesive Zone Model* (CZM) [10-12], *Continuum Damage Mechanics* (CDM) [8-9,13-14], and *lattice models* [15]. Both CZM and CDM are well-researched in the field of advanced numerical analysis of timber structures, while analysis with lattice models is mostly used in mesoscopic and microscopic fields of timber study.

While many studies have employed CDM to model the brittle behaviour of timber e.g. [8-9,13-14], the method has the disadvantage of not being able to show permanent deformations in the analysis as well as being mesh dependent with convergence problems when used in implicit code [7, 14]. As permanent deformations are essential for the analysis of the reusability of the joint, the material model presented has utilised fracture mechanics with cohesive zone modelling (CZM) to model the brittle behaviour of timber. Using CZM has the disadvantage of requiring predefined fracture surfaces, but as these fracture planes are predictable for the *ReconWood* joint, the method fits well.

Two different modes can initiate a fracture in a Cohesive Zone Model: tensile stresses acting perpendicular to the fracture plane (mode I); and tangential stresses acting parallel to the fracture plane (mode II) [16]. In this study the fracture has been restricted to mode II as only this type of failure is expected in the fracture plane. Despite it being possible to define both failure modes, including mixed-mode fracture, it is undesirable unless necessary as CZM requires substantial computational time.

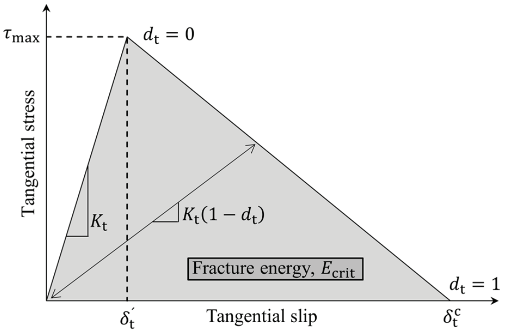

Figure 5: *Cohesive Zone Modelling, CZM, for mode II*

The progressive failure of a Cohesive Zone Model is expressed by a bilinear stress-slip law as shown in Figure 5. Damage is initiated at $\delta_t' \ (d_t = 0)$ and is completed at $\delta_t^c \ (d_t = 1)$ when the stress reaches zero value. Any further tangential slip occurs without any tangential stress.

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3.3 MODELLING THE DUCTILE BEHAVIOUR

In the literature, the compressive behaviour of timber is often modelled as an anisotropic plastic behaviour using a single surface yield function, such as the *Hill Criterion* [10,17], the *Hoffman Criterion* [18], or the *Tsai-Wu Criterion* [19]. A popular alternative is to implement these yield functions as failure criteria within continuum damage mechanics (CDM) [8,9]. This enables the modelling of both strain hardening and softening by modifying the stiffness matrix. However, utilising CDM shows some drawbacks as mentioned in Section 3.2.

Both the Hoffman Criterion and the Tsai-Wu Criterion are modifications of the Hill Criterion introducing separate yield stresses for tension and compression. The Hoffmann Criterion obtains the capability of differentiating yield stresses in tension and compression by including terms that are linear on the stress. The Tsai-Wu Criterion extends this further by the addition of a parameter that accounts for interactions of normal stresses. [7,20] However, as each criterion expands in complexity, so does the application in commercial FE software. The *ReconWood joint* analysed in this paper is not expected to be subjected to noteworthy tensile stresses so applicability is prioritised and the Hill Criterion is utilised. The post-peak behaviour in compression is thus simplified to being ideally plastic, neglecting the direction-dependent hardening and softening.

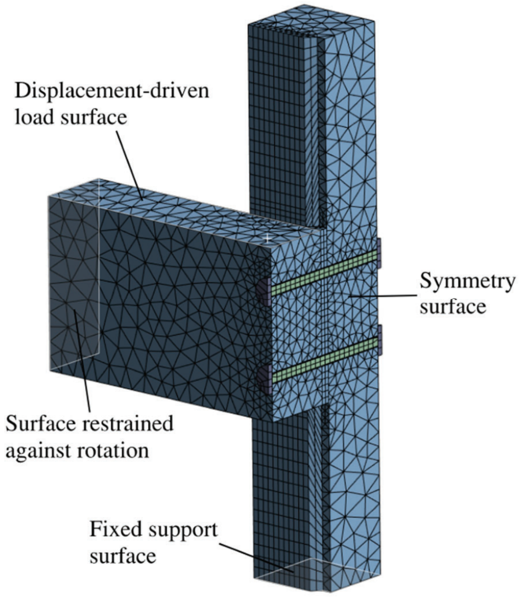

Figure 6: *FEM model with boundary conditions.*

4 FINITE ELEMENT MODEL

The aim of the FEM model is to predict the load-carrying capacity, stiffness, failure mechanism, and reusability of a *ReconWood joint*. The proposed material model is implemented in *Ansys Mechanical* for FEM analysis of the joint.

4.1 GEOMETRY

The joint in question connects two orthogonal timber blocks as used when constructing lattice structures such as that shown in Figure 2. The FEM model, Figure 6, comprises a horizontal timber block containing the male shear key part and a vertical timber block containing the female part. Dimensions of the horizontal block can be seen in Figure 7, while the vertical block is modelled as a perfect negative of the horizontal. The blocks are held together by M5 steel bolts.

4.2 BOUNDARY CONDITIONS, CONTACT DEFINITION, AND MESHING

The model is intended to represent a subpart of a larger lattice structure consisting of multiple *ReconWood joints.* When used in this manner the joints will solely transfer shear forces. Hence the FEM model is designed to investigate the joint in a state of pure shear. This is done by applying the boundary conditions shown in Figure 6.

Interaction between both the timber elements and the bolts and timber are defined by a frictional surface contact with a friction coefficient of 0.2.

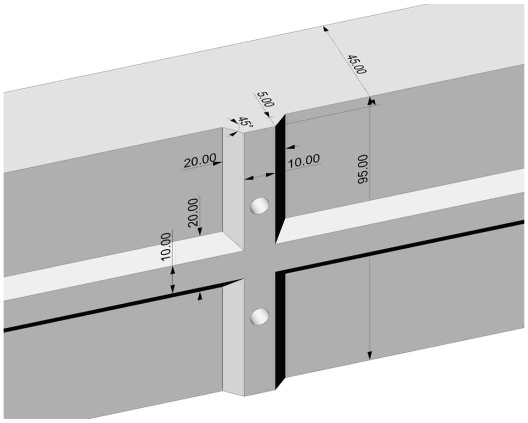

Figure 7: *Geometry of the shear key in the considered ReconWood joint*

The model is discretised with a combination of *tetrahedral* and *hex-dominant* meshes as seen in Figure 6. Generally, the parts are meshed with a size of 8 mm, while the contact surfaces are reduced to 4 mm with a fast transition. A mesh sensitivity study was carried out to balance accuracy and computing resources satisfactorily.

To decrease computational time, a vertical plane of symmetry is used.

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Property	Reference	Mean value
Bending strength	Material testing	46.9 MPa
Bending modulus of elasticity, ∥	Material testing	16.3 GPa
Density	Material testing	431 kg m^{-3}
Compressive strength, ∥	[21]	29 MPa
Compressive strength, ⊥	[21]	3.0 MPa
Shear strength	[21]	6.3 MPa
Shear strength, rolling	[26]	1.2 MPa
Bending modulus of elasticity, ⊥	[21,22]	0.54 GPa
Shear modulus	[21,2]	1.0 GPa
Shear modulus, rolling	[28]	0.05 GPa
Poisson's ratio, LR	[8]	0.45
Poisson's ratio, LT	[8]	0.45
Poisson's ratio, RT	[8]	0.50
Tangential fracture energy	[29]	1200 J m^{-2}
Tangential fracture energy, rolling	[29]	600 J m^{-2}

Table 1: *Mechanical properties of C24 determined by material testing and literature. ⊥ denotes properties perpendicular to the fibre direction. ∥ denotes properties parallel to the fibre direction. L, R, and T denote longitudinal, radial, and tangential respectively.*

4.3 IMPLEMENTING THE MATERIAL MODEL

The material model is implemented by utilising the built-in material laws provided by Ansys' *Engineering Data.* This is done in two steps. (*i*) The timber blocks are assigned a material defined by *Hill Yield Criterion;* (*ii*) CZM is included by defining a fracture surface on the back of the shear key as seen in Figure 8. This surface is assigned a *Fracture Energy Debonding* material for mode II debonding.

This two-step implementation enables a distinguishment between two possible failure modes and gives the option to evaluate the level of damage to the joint by analysing both the plastic strains from compression and the damage evolution on the CZM surface from shear.

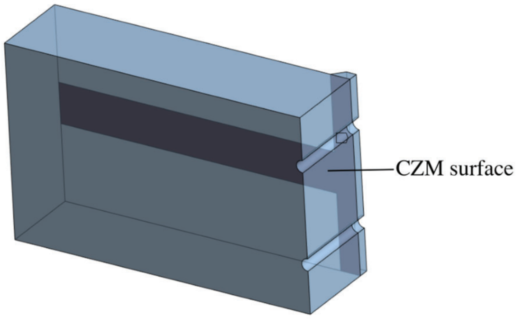

Figure 8: *Predefined fracture surface in FEM model*

4.4 MATERIAL PROPERTIES

The material properties of the timber blocks are based on the verification experiments presented in Section 5. Where applicable, the material properties are determined based on the procedure outlined in EN 384 [21] and JCSS Probabilistic Model Code Part 3 [22], while the remaining properties are based on values found in the literature. The bending strength, the bending modulus of elasticity, and the density are determined experimentally in accordance with EN 408 [23], whereupon these three properties are used to estimate the majority of the remaining properties. The material properties used in the FEM model are given in Table 1 along with a reference to how the properties were determined. For properties determined using EN384 [21], mean reference properties are used as input in the formulas given in the standard. This is in accordance with the procedure presented in [7]. Using this method also proves to yield reasonable results by comparison with experimental data found in literature e.g. [24].

Neither EN 384 [21] nor JCSS Probabilistic Model Code Part 3 [22] give an estimate of the rolling shear strength, rolling shear modulus or Poisson's ratios. The rolling shear strength is highly discussed in the literature [7,25,26]. EN1995 [26] specifies the rolling shear strength to be approximately twice the tensile strength perpendicular to the fibre direction. This yields a mean strength of 1.2 MPa. This lies well inside the range of values that is normally suggested in other literature, therefore this value is used. Most literature suggests a rolling shear modulus of 50 MPa [7]. Hence, this is the value adopted for this model. The Poisson's ratios are often set in the range of 0.3-0.5 [7,8,27]. Values of $\nu_{LR} = 0.45$, $\nu_{LT} = 0.45$ $\nu_{RT} = 0.50$ are used in this analysis, as suggested in [8].

The bolts are assigned an isotropic linear-elastic material with Young's modulus = 210 GPa and Poisson's ratio = 0.3.

5 EXPERIMENTS

In order to verify the FEM model presented in Section 4, a test series with the same *ReconWood joint* was conducted. The test series consisted of three identical joints with the same material properties and geometry as implemented in the FEM model.

5.1 PRODUCTION OF THE TEST SPECIMENS

The specimens were fabricated using a KUKA KR240 R3330 industrial robot arm equipped with a 12 kW rotary spindle. The employed robot arm has an additional "absolute accuracy" feature, which assures precise dimensions and geometry of the milled specimen, and therefore a desired tight fit of the male and female parts of the joints.

Three milling tools were exchanged during the fabrication process to produce the cross-shaped joints, utilising automatic tool change. Firstly, the 6 mm holes were drilled, generating some extra space around the M5 bolts. This was desired both for facilitating the automated robotic assembly process as well as for the performance of the joints. Secondly, a V-shaped tool with a 45° inclination blade was used to achieve the inclined sides of the cross geometry in a single cut, and finally, a flat end mill was to clear out the left material and even out all the horizontal sides of the joint.

5.2 TEST SETUP

The experiments were performed with a Zwick/Roell Z050 testing machine, applying a deformation-controlled load at 1.2 mm/min.

The test setup is shown in Figures 9 and 10. To obtain shear in an orthogonal joint, three timber elements were used. The vertical element of the joint was installed in a specially designed steel shoe and connected to the horizontal element by the *Reconwood joint* with M5 bolts. A vertical load-transferring element was likewise installed in a steel shoe and placed on top of the horizontal element. To ensure that the tests were performed in pure shear the load was applied on two knobs located directly in the joint's shear plane.

To eliminate the effects of bending and torsional moments in the joint, two bolts were used instead of one and the horizontal element was restrained against rotation by using two nail plates.

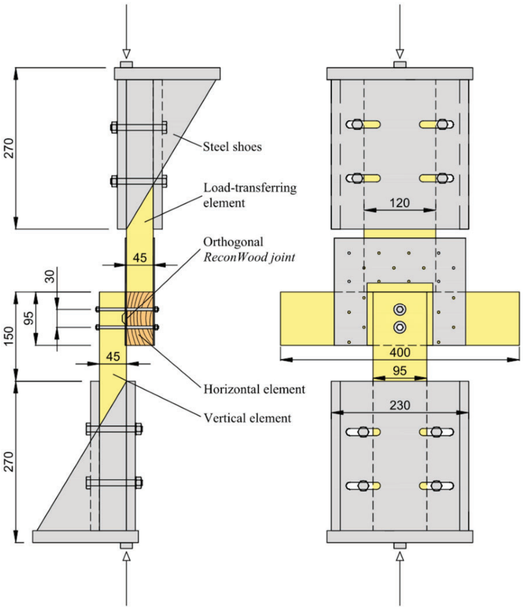

Figure 9: *Test setup, schematisation*

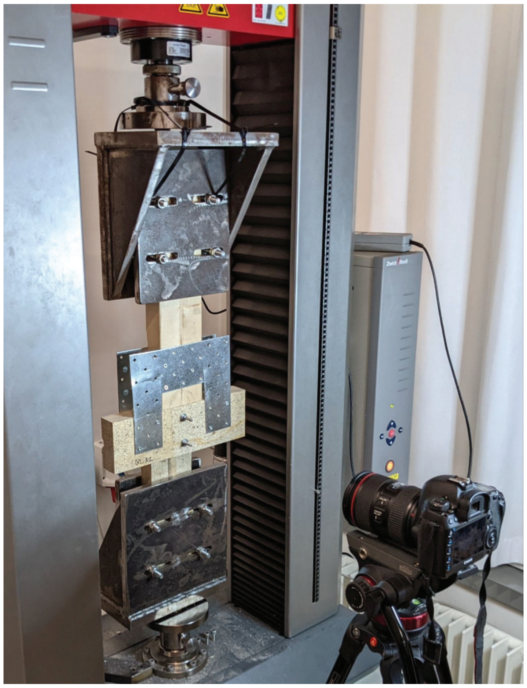

Figure 10: *Test setup, photo*

6 RESULTS AND COMPARISON

The FEM model is evaluated by comparison with the experimental findings, namely by: (*i*) the observed failure mechanism and (*ii*) the force-displacement response.

Additionally, the FEM model presents the option to analyse the reusability. As no evaluation of the reusability was done in the experiments, no comparison can be made. However, an assessment of the joint's reusability is made based on the FEM model and previous studies of the *Reconwood joint*.

6.1 FAILURE MECHANISM

Despite the similarity of the test specimens, two failure mechanisms are observed. The failure mechanisms are *FM1* - local compressive failure; *FM2* - shear cut-off. FM1 corresponds to a situation where the compressive strength is insufficient to carry the load without introducing irreversible deformations. FM2 corresponds to a situation where the shear strength of the keys is insufficient to carry the load, and thus the shear keys are (partly) cut off.

In the FEM model, the failure mechanism is evaluated based on the damage level at the fracture surface. FM1 is defined as the situation where the damage coefficient, d_t, has reached a value of 1 acc. Figure 5. All other situations are interpreted as FM2.

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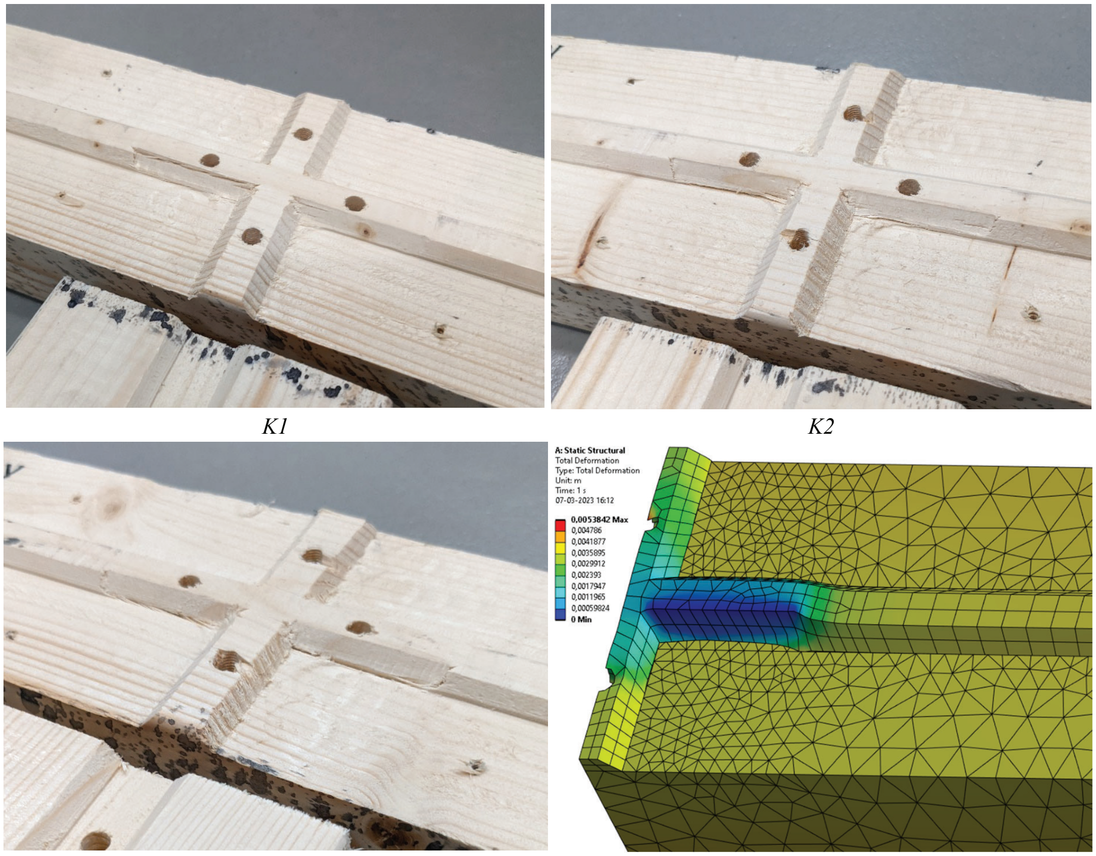
K1 *K2*
K3 *FEM results*

Figure 11: *Failure mechanisms found in the experimental testing and FE analysis*

For the tests, the failure mechanisms are evaluated qualitatively by visual inspection. The failure is classified as FM2 when apparent failure cracks are visible.

The observed failure mechanisms for both the FEM model and the experiments are listed in Table 2 and shown in Figure 11.

Test	FEM model	Experiments
K1	FM2	FM1/FM2
K2		FM2
K3		FM2

Table 2: *Failure mechanisms in FEM model and experiments*

6.2 FORCE-DISPLACEMENT RESPONSE

The force-displacement response curves of the numerical analysis along with the results from the experiments are shown in Figure 12. In this comparison, the weight of the test setup is included in the response of the experiments, which results in an initial load at $d = 0$ mm.

It is seen that the FEM model shows great accuracy in predicting the response of the *ReconWood joint*.

The force-displacement response curves in Figure 12 show that this type of timber joint displays a large degree of nonlinear behaviour when subjected to shear. This corresponds well with the findings in [2] which analysed an earlier generation of the *ReconWood joint*.

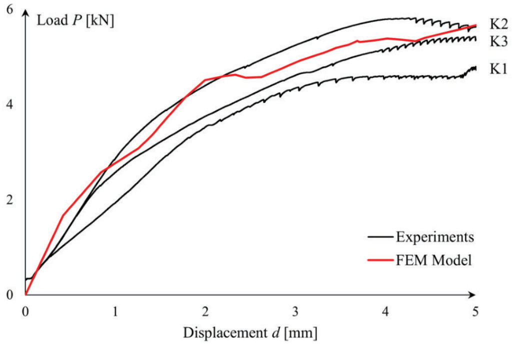

Figure 12: *Force-displacement response curves for the FEM model and the experiments*

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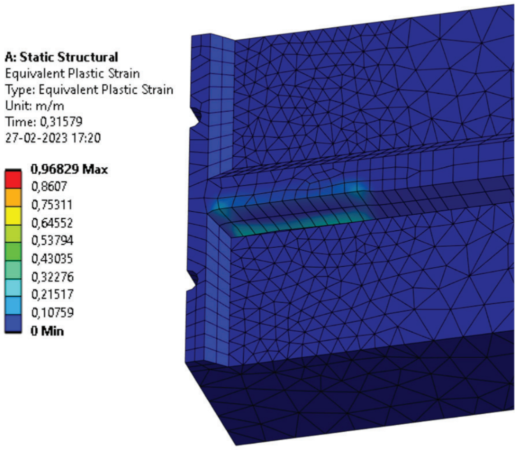


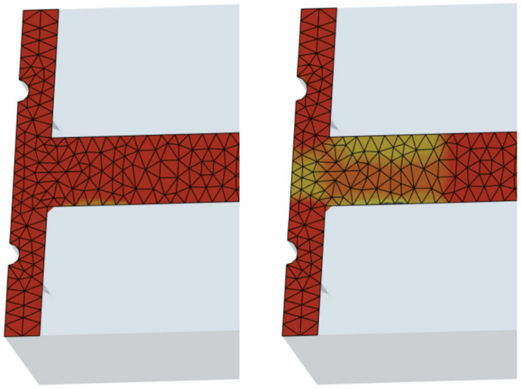
Figure 13: *Plastic strains at 3.4 kN load*

6.3 REUSABILITY

The FEM model presents the option to analyse the reusability in two ways: by permanent deformations of the timber material due to compression and by damage initiation and evolution of the CZM material due to shear.

A qualitative assessment of the reusability of the joint is presented. In Figure 13, the maximum plastic strains at 3.1 kN load are shown as the point of acceptable permanent deformations. Figure 14 shows the damage evolution of the CZM material at 4.4 kN and 5.0 kN, respectively showing the brittle failure from shear. It is seen that approximately no damage is seen at 4.4 kN before a fast escalation of damage. The threshold for reusability of the joint is set at 3.1 kN.

In earlier studies of the first generation of the *ReconWood joint,* a recommendation of 50%-60% of the ultimate capacity was proposed as a threshold for reusability [30]. By studying the FEM model it is found that this threshold gives a good indication of the reusability. The average ultimate capacity of the experiments was found to be 5.48 kN, setting the threshold for reusability at 57%.



(i) *(ii)*

Figure 14: *Damage evolution on CZM material at (i) 4.4 kN and (ii) 5.0 kN load. Damage under $d_t = 1$ is marked in red; damage at $d_t = 1$ is marked in orange and yellow*

7 CONCLUSIONS

The present paper outlines a method for performing structural analysis of a complex timber joint using FEM along with an experimental verification. Focus has been given to developing a reliable model that can predict the mechanical response while being easily implementable in widely available FE software. This is achieved through a hybrid material model which combines two methods for capturing the complex anisotropy of timber. The ductile behaviour seen in compression is modelled as a single yield surface using the Hill Criterion, and the brittle behaviour from shear by fracture mechanics is modelled with Cohesive Zone Modelling (CZM).

The FEM model is able to predict the failure mechanism observed in the experiments satisfactorily, capturing the failure of the shear keys seen in experiments. Moreover, the model depicts the force-displacement response highly satisfactorily, capturing the stiffness degradation and nonlinear behaviour seen in experiments. The proposed model is highly implementable in conventional FEM software, which sets it apart from more advanced methods, making it accessible and useful for practical engineering applications. The simplicity in the material modelling ensures furthermore a low computational time which facilitates the modelling approach can be upscaled to an analysis of a larger structure with multiple joints.

The present study has been limited to one specific joint, and further experimental and analytical studies are necessary to investigate the applicability and validity of the proposed method to different joint configurations. Additionally, the reusability of the joints was not assessed during the tests; thus, a more comprehensive experimental program is required to expand the scope of the study and investigate the threshold for reusability of the proposed model.

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