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AN INNOVATIVE STEEL-CLT SHEAR CONNECTOR: DEVELOPMENT AND EXPERIMENTAL-NUMERICAL INVESTIGATION

Summary: This paper presents the development of an innovative steel-cross laminated timber (steel-CLT) shear connector designed for efficient shear transfer. The structural performance and mechanical behaviour of the proposed system were comprehensively evaluated through experimental testing and numerical modelling. Push-out tests were conducted to evaluate the load-carrying capacity, stiffness, and failure modes under static loading. Additionally, a three-dimensional finite element model was developed to simulate the nonlinear response, material behaviour, and contact mechanics between the steel components and timber layers. The numerical model was validated against experimental results, showing strong agreement in terms of load-displacement behaviour and ultimate capacity. The findings demonstrate that the proposed connection achieves high strength and ductility, offering a promising solution for composite steel-timber structures.

Keywords: shear connector, steel, CLT, experimental testing, finite element analysis

INOVATIVNI MOŽDANIK ZA SPREZANJE ČELIKA I ULD-A: RAZVOJ I EKSPERIMENTALNO-NUMERIČKO ISTRAŽIVANJE

Rezime: U radu je prikazan razvoj inovativnog moždanika za sprezanje čelika i unakrsno lameliranog drveta (čelik-ULD) namenjenog efikasnom prenosu smicanja. Mehaničko ponašanje i odziv predloženog sistema sveobuhvatno su određeni putem eksperimentalnog ispitivanja i numeričkog modeliranja. Sprovedeni su testovi smicanja moždanika kako bi se ocenili nosivost, krutost i mehanizmi loma pri statičkom opterećenju. Pored toga, razvijen je trodimenzionalni model konačnih elemenata za simulaciju nelinearnog odziva, ponašanja materijala i kontaktne analize između čeličnih komponenata i slojeva drveta. Numerički model je verifikovan na osnovu eksperimentalnih rezultata, pri čemu je pokazano dobro poklapanje u pogledu ponašanja opterećenje-klizanje i granične nosivosti. Dobijeni rezultati pokazuju da predloženi moždanik ostvaruje veliku nosivost i duktilnost, predstavljajući perspektivno rešenje za primenu u spregnutim konstrukcijama od čelika i drveta.

Ključne reči: moždanik, čelik, ULD, eksperimentalno ispitivanje, MKE analiza

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1. INTRODUCTION

Contemporary trends in civil engineering increasingly direct design practice towards sustainable, environmentally friendly, and energy-efficient materials, with timber and engineered wood products taking centre stage. The development of cross-laminated timber (CLT) has represented a major breakthrough in multi-storey timber construction, enabling longer spans to be bridged and substantial loads to be sustained [1]. However, owing to the relatively low mass and limited modulus of elasticity of timber compared to steel, timber panels alone often fail to satisfy the rigorous criteria of Serviceability Limit States (SLS), such as deflections and vibrations [2]. On the other hand, steel profiles are characterised by exceptionally high tensile and compressive strength as well as a high modulus of elasticity, but are susceptible to local and global buckling issues. Combining steel and CLT into a unified composite structure produces a synergistic effect that maximally exploits the positive mechanical properties of both materials while mitigating their respective drawbacks.

Steel-CLT composite beams operate on the principle of transferring longitudinal shear forces across the contact interface between the steel section and the timber panel. The fundamental prerequisite for two distinct materials to act as a unified composite structure is the provision of a reliable and sufficiently stiff connection using mechanical fasteners – shear connectors. The mechanical behaviour of these shear connectors, quantified by their initial slip modulus K_s and ultimate load capacity F_{max}, directly governs the degree of stress redistribution across the depth of the beam cross-section and determines whether the system exhibits complete or partial composite action.

The theory of composite structures distinguishes between two boundary states of composite action:

- Rigid composite action: Characterised by negligible relative slip across the joint interface. In this case, the composite cross-section achieves maximum possible flexural stiffness, with plane sections remaining plane after deformation in accordance with the Bernoulli hypothesis.
- Flexible composite action: Occurs when shear connectors possess finite elastic compliance, leading to the development of slip between the steel and timber components. This slip induces a discontinuity in the strain distribution across the interface, thereby reducing the overall load-carrying capacity and increasing the deflection of the composite element compared to a fully composite system.

To achieve efficient steel-CLT composite action in engineering practice, shear connectors are subjected to two often contradictory requirements [3]:

- High initial slip modulus (K_s): Essential at serviceability load levels (Serviceability Limit States – SLS) to prevent interface slip, minimise deflections, and ensure a monolithic structural response of the beam.
- High post-elastic ductility with minimal secondary stiffness ($K_t \approx 0$): Necessary within the Ultimate Limit States (ULS) domain to enable substantial plastic deformations prior to failure. This ductility ensures the plastic redistribution of shear forces among the group of connectors and prevents sudden, brittle failure of the timber panel, as well as the composite beam as a whole.

Traditionally, standard dowel-type mechanical fasteners, such as bolts [4], inclined self-tapping screws [5], and glued-in rods, are applied in steel-timber connections. Bolts are exceptionally popular due to their low cost, ease of installation, and markedly ductile response resulting from the formation of plastic hinges in the steel shank. However, the primary drawback of bolts is their low initial shear stiffness and modest load-carrying capacity, owing to the small bearing area of the bolt shank against the timber fibres [6]. During force transfer, the timber surrounding the hole is subjected to severe compressive stresses, leading to early crushing of the timber fibres along the hole perimeter even under low load levels. Achieving full composite action with conventional bolts requires an excessively dense fastener spacing, which compromises the structural integrity of the CLT panel and drastically increases labour costs.

At the same time, bonded connections [7], punched metal plates [8], and epoxy resin reinforcements [9] provide exceptionally high initial stiffness; however, they suffer from brittle failure modes, alongside extremely stringent quality control requirements during site execution.

To bridge the gap between the low stiffness of conventional bolts and the brittle failure modes of rigid bonded connections, an innovative reinforced shear connector solution is proposed in this study. The primary objective of this work is a comprehensive experimental and numerical investigation of the proposed solution through:

- Experimental evaluation of the load-carrying capacity and stiffness of unreinforced (Series S1) and reinforced specimens (Series S2 and S3) via push-out tests, conducted according to the procedure specified in the SRPS EN 26891 standard [10].
- Development, verification, and validation of a new, computationally efficient hybrid FE model of the timber and the shear connector as a whole, overcoming the complexity and convergence issues inherently present in continuum timber models found in the literature [11,12].

2. MATERIALS AND METHODS

2.1. GEOMETRY AND CONCEPT OF THE REINFORCED SHEAR CONNECTOR

The new shear connector solution is conceptualised with the objective of significantly increasing the initial elastic stiffness (K_s) and ultimate load-carrying capacity (F_{max}), while preserving the ductile failure mechanism characteristic of dowel-type fasteners. The concept relies on inserting a specially shaped reinforcing element – fabricated from sheet steel (4 mm thick and 15 mm wide) – into a pre-cut curved groove within the CLT panel (Figure 1).

The reinforcing element, shaped as a circular segment, is positioned in the zone directly ahead of the M10 (Grade 8.8) bolt shank. Its primary role is to transform the concentrated contact pressure from the bolt shank and distribute it over a significantly larger surface area of the timber fibres within the CLT panel. In doing so, it:

- Reduces local contact stresses to prevent early timber crushing, while engaging a larger timber volume under compression to increase initial stiffness (K_s) and ultimate capacity (F_{max}).
- Ensures high ductility through the progressive yielding and bending of both the reinforcing element and the bolt at large slip displacements, without the risk of brittle timber failure.

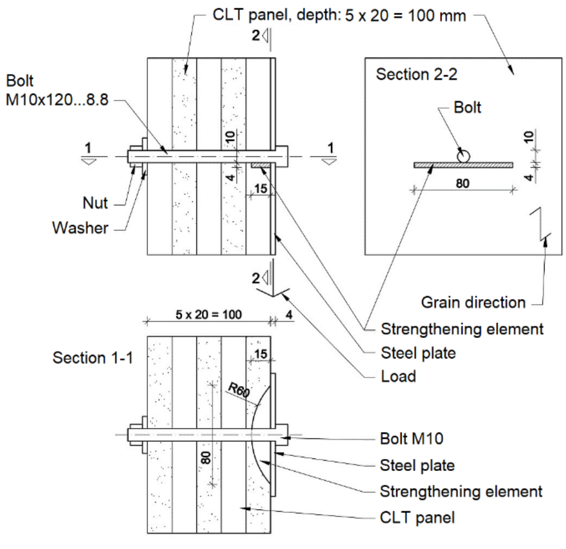


Figure 1: Arrangement of the bolt and steel reinforcing element in the steel-CLT shear connector [13]

2.2. DETAILED CHARACTERISATION OF THE MATERIALS USED

Reliable numerical modelling and interpretation of experimental results require the accurate prior determination of the mechanical properties of all constituent materials.

2.2.1. Steel Components

Three distinct steel materials were utilised in this study, with their mechanical properties determined via axial tensile tests:

- Structural steel S235: Applied for the fabrication of the reinforcing elements in Series S2. The experimentally determined yield strength was f_y = 250 MPa, and the ultimate tensile strength was f_u = 335 MPa.

- Structural steel S275: Applied for the fabrication of the reinforcing elements in Series S3 and the cold-formed profile serving as the steel composite section. The experimental values obtained were f_y = 325 MPa and f_u = 460 MPa.

- Bolt steel (grade 8.8): Tensile testing determined a yield strength of f_{yb} = 760 MPa and an ultimate tensile strength of f_{ub} = 850 MPa.

2.2.2. CLT Panels and Timber Testing

Five-layer CLT panels with a total thickness of 100 mm (five 20 mm layers) made of Norway spruce (*Picea abies*), declared strength class C24 [14], were used to fabricate the connection specimens.

To obtain input parameters for the hybrid timber FE model, a series of experimental tests was conducted on specimens cut from the CLT panels:

- Density and moisture content: Moisture content determination via the oven-dry method revealed an average moisture content of 9% for the CLT panels, with a mean density of 458 kg/m^3. For the solid timber strength testing specimens, the measured moisture content was 10.5%, with a density of 420 kg/m^3.

- Embedment strength parallel to the grain (Figure 2a): Evaluated on specimens featuring a 10 mm diameter hole, yielding a mean value of $f_{h,0,mean}$ = 19.9 MPa at a deformation level of 5 mm, and 22.1 MPa at 15 mm.

- Embedment strength perpendicular to the grain (Figure 2b): The recorded mean value was $f_{h,90,mean}$ = 17.2 MPa at 5 mm deformation, and 26.8 MPa at 15 mm.

- Washer indentation perpendicular to the grain (Figure 2c): The timber resistance during the penetration of an M10 washer (outer diameter 30 mm) into the CLT outer layer was determined. At an ultimate indentation depth of 5 mm, the compression resistance reached 15 MPa.

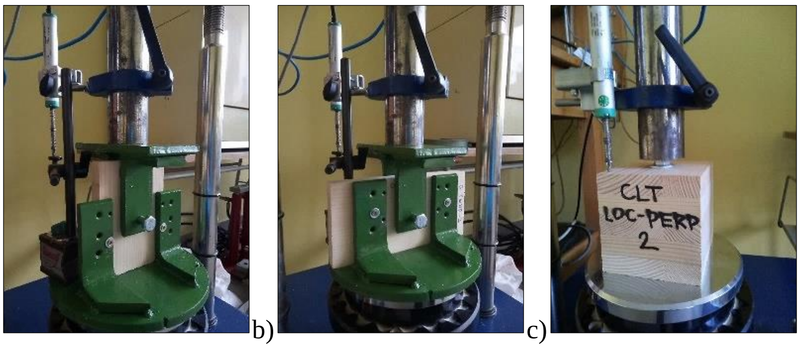
a) 

Figure 2: Determination of the mechanical properties of timber (CLT) [3]:
a,b) embedment strength parallel and perpendicular to the grain, c) washer indentation

2.3. EXPERIMENTAL TESTING OF SHEAR CONNECTORS: ASYMMETRICAL PUSH-OUT TEST

The evaluation of connector load-carrying capacity and stiffness was carried out using an asymmetrical push-out test, incorporating lateral restraint on the fixed part of the specimen [15]. Although the Eurocode 4 standard prescribes a symmetrical push-out test, asymmetrical testing offers significant advantages in steel-timber shear connections: a 50% reduction in material consumption, a simplified instrumentation setup, and the direct measurement of the force per connector without assuming an equal load distribution across a group of connectors [16, 17].

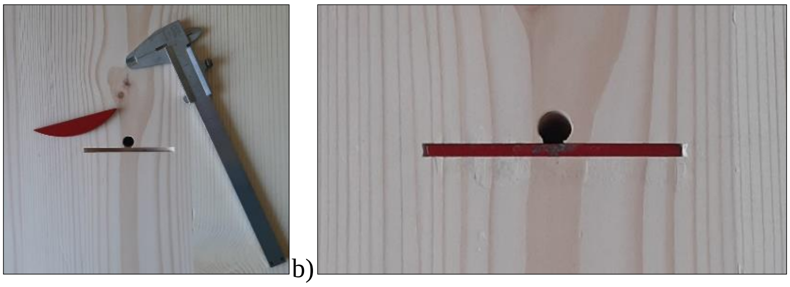
2.3.1. Specimen Geometry and Preparation

Three series comprising six specimens each (a total of 18 connections) were tested:

- Series S1 (control): Consists of a 300 mm long cold-formed steel profile and a CLT panel with dimensions of 300×300×100 mm. The connection was executed using a single M10 bolt equipped with a washer and nut. The nut was placed on the CLT panel side to ensure that the unthreaded bolt shank passed through the shear plane.

- Series S2 (with S235 steel reinforcing element): In addition to the S1 configuration, a 15 mm deep groove was cut into the outer layer of the CLT panel using a circular saw, into which a 4 mm thick S235 steel reinforcing element was embedded (Figure 3).

- Series S3 (with S275 steel reinforcing element): Geometrically identical to Series S2, but with the reinforcing element fabricated from higher-strength S275 steel.



a) b)

Figure 3: Groove in the CLT panel and the reinforcing element [3]:
a) before assembly, b) after assembly

2.3.2. Test Setup and Procedure

Testing was performed using an electromechanical testing machine with a 50 kN capacity. The specimen was positioned in a specially designed rigid steel frame that prevents lateral instability of the specimen during the application of vertical load.

The loading protocol was implemented strictly in accordance with SRPS EN 26891 [10]:

- Phase 1: The first specimen of each series (S1-1, S2-1, S3-1) was subjected to monotonic loading up to failure to determine the estimated maximum load, F_{est}.

- Phase 2 (subsequent specimens): The load was increased to 0.40 F_{est} and held constant for 30 seconds (Figure 4a,b).

- Phase 3: The load was reduced to 0.10 F_{est} and maintained for 30 seconds.

- Phase 4: Monotonic loading was applied until failure or until reaching a maximum slip displacement of 15 mm.

Relative slip at the shear plane was continuously recorded using two Linear Variable Differential Transformers (LVDTs), symmetrically positioned on both sides of the specimen at the bolt axis level (Figure 4c).

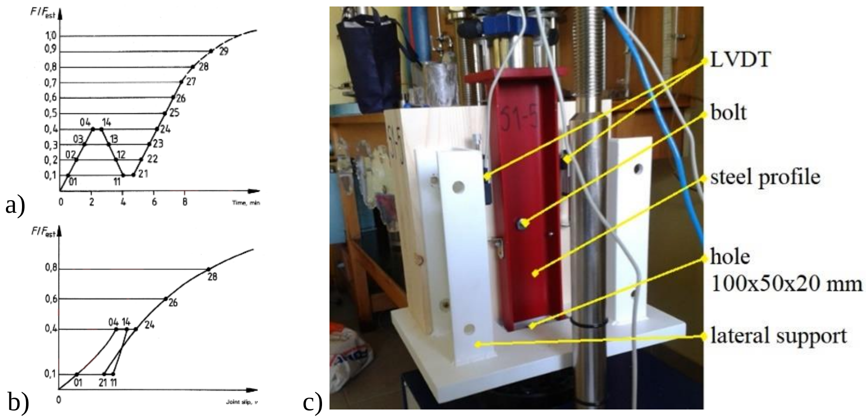


Figure 4: a,b) Testing procedure according to SRPS EN 26891 [10],
c) asymmetrical push-out specimen under load [3]

2.4. NUMERICAL FE MODELLING

The nonlinear finite element (FE) analysis was performed in the Femap with NX Nastran software package [18] through nonlinear static analysis (SOL 601 / Advanced Nonlinear Static).

2.4.1. Hybrid Timber Modelling Concept

The formulation of 3D continuum timber models with damage [11] requires the definition of a large number of independent material constants (elastic moduli, shear moduli, Poisson's ratios, and strength parameters in all directions). In addition to difficult experimental calibration, such models routinely suffer from convergence failures at moderate deformations due to numerical singularities in the steel-to-timber contact zone.

To overcome these issues, a novel hybrid timber modelling approach was formulated [4]:

- The volume of timber in the vicinity of the bolt hole and groove was replaced by a system of equivalent 2-node line (ROD) elements oriented along the direction of the shear force (z-axis) (Figure 5a).

- The elements were assigned a bilinear constitutive model with elastoplastic hardening, defined based on the results of embedment tests and washer indentation tests (Figure 5b).

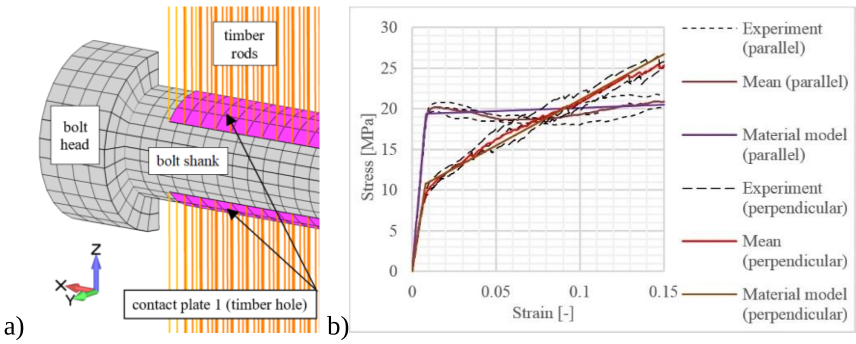


Figure 5 [3, 4]: a) Bolt and timber FE (ROD and PLATE),
b) Stress-strain curves for timber ROD elements

- To transfer compressive loads from the 3D SOLID elements of the bolt and reinforcing element to the ROD elements of the timber, contact shells were defined, composed of 4-node surface (PLATE) elements with negligible thickness (t = 0.10 mm) and elastic modulus

(E = 0.001 GPa). The contact shell serves exclusively as a geometric intermediary, without introducing artificial stiffness (Figure 5a – contact plate 1).

2.4.2. Meshing and Boundary Conditions

Advantage was taken of the specimen symmetry with respect to the xOz plane; thus, half of the connection was modelled applying the corresponding symmetry boundary conditions.

The meshing of individual components was carried out as follows (Figure 6):

- Bolt: Modelled as a single body (shank+head+nut) using 8-node hexahedral (SOLID) finite elements. A mesh sensitivity analysis was conducted by dividing the bolt diameter into 4, 6, and 8 elements (FE sizes: 2.5 mm, 1.67 mm, and 1.25 mm, respectively).

- Cold-formed profile: Only the profile web was modelled, which was divided into an elastoplastic zone around the hole (zone width 5d = 50 mm) and an elastic zone. The stiffening effects of the profile flanges were represented by a system of rigid ROD elements that prevent web buckling during deformation.

- Reinforcing element: Meshed using SOLID elements with outer edge rounding applied at a radius of r = 1.0 mm. This edge rounding prevented the penetration of sharp corners into the contact shells and ensured numerical convergence, while altering the geometric section properties to a negligible extent (moment of inertia variation was under 3.5%).

A total of 10 surface-to-surface contact pairs were defined based on Coulomb’s law of friction (μ = 0.35 for steel-to-timber and μ = 0.20 for steel-to-steel contacts [3]). The load was applied in 200 equal increments.

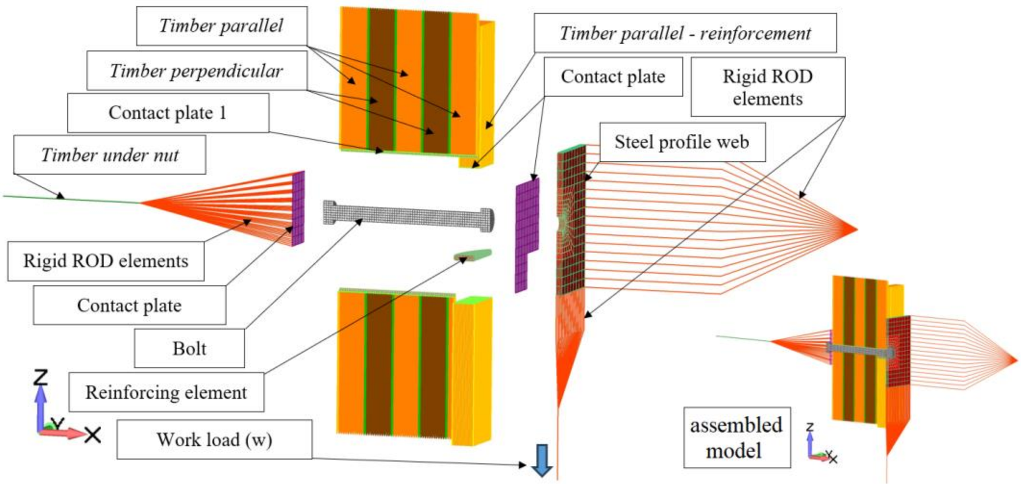


Figure 6: Numerical FE model components of the considered dowel-type fastener [3]

3. RESULTS AND DISCUSSION

3.1. ANALYSIS OF EXPERIMENTAL RESULTS

Shear connectors from all three tested series exhibited high stability and repeatability of results. The scatter of the measured ultimate load values (F_{max}) within the same series was remarkably low (under 4%), whereas the scatter of the slip modulus (K_s) reached up to 28%, which is typical for experimental testing of timber structures due to the inherent variability of wood properties.

The mean values of ultimate load and initial slip modulus, determined in accordance with the SRPS EN 26891 methodology, are presented in Table 1.

Table 1: Comparative analysis of the experimental results for Series S1, S2 and S3

Parameter	Series S1	Series S2	S2/S1-1 [%]	Series S3	S3/S1-1 [%]
F_{max} [kN]	17.65	29.01	64%	27.16	54%
K_s [kN/mm]	3.98	9.63	142%	13.54	240%
Failure slip [mm]	> 15.0	> 15.0	-	> 15.0	-

From the results, the key effects of incorporating the reinforcing element can be observed:

- Drastic increase in initial stiffness: The introduction of the reinforcing element fabricated from S235 steel (Series S2) resulted in a 142% increase in the slip modulus, whereas with S275 steel (Series S3), this increase reached 240%. The reinforcing element successfully transmits the dominant portion of the shear force in the early loading stage and distributes it over a significantly larger contact area with the CLT, preventing large initial joint slip.

- Substantial increase in ultimate load: The load-carrying capacity of the connection was increased by 64% for Series S2, and by 54% for Series S3. Interestingly, the series reinforced with lower-grade steel (S235) achieved a slightly higher ultimate load compared to Series S3 (S275), which could be attributed to the occurrence of the rope effect in the reinforcing element.

- Preservation of exceptional ductility: All three series endured the complete prescribed slip of 15 mm without a sudden drop in load-carrying capacity or splitting of the CLT panel. The pronounced post-elastic range confirmed that the inclusion of the steel reinforcing element did not compromise the ductile failure mode of the bolt.

3.2. COMPARISON OF EXPERIMENTAL AND FEA RESULTS

Verification of the formulated numerical FE model was carried out through a mesh sensitivity analysis using different mesh densities. The numerical FE model was validated by comparing the numerical results with the experimental test data for all three series. The results are presented in Table 2.

Table 2: Comparison of experimental and FEA results with percentage deviations

Parameter	Mesh density	Series S1	Series S2	Series S3
$F_{max,exp}$ [kN]	-	17.65	29.01	27.16
$F_{max,FEM}$ [kN]	coarse (2.5 mm)	17.63	28.59	29.56
	medium (1.67 mm)	17.69	28.62	29.48
	fine (1.25 mm)	17.72	29.36	30.19
$(F_{max,exp}/F_{max,FEM})$-1 [%]	medium (1.67 mm)	+0.2%	-1%	+9%
$K_{s,exp}$ [kN/mm]	-	3.98	9.63	13.54
$K_{s,FEM}$ [kN/mm]	medium (1.67 mm)	3.93	7.83	9.31
$(K_{s,exp}/K_{s,FEM})$-1 [%]	medium (1.67 mm)	-1%	-19%	-31%

From the comparative analysis, it can be deduced that the numerical model predicts the shear connector load-carrying capacity with high accuracy (max. deviation 9%). The deviations in slip moduli for the reinforced series (1–31%) originate from the assumed bilinear idealisation in the hybrid timber model, yet remain within acceptable limits for engineering practice.

Comparison with models from the literature. The proposed hybrid timber FE model demonstrated significantly superior performance compared to existing continuum models from the literature:

- *Sandhaas* model [11]: A continuum timber model applied to a steel-to-timber dowel joint yielded a 12% deviation between the FE and experimental load-carrying capacity, with an internal scatter of 13% in the sensitivity analysis. Furthermore, the model suffered from convergence failure at a slip of less than 5 mm.

- *Hassanieh* model [12]: The aforementioned material model, applied to a screwed steel-to-CLT connection, exhibited a 15% deviation in load-carrying capacity relative to experimental results and an internal scatter of 22% in the sensitivity analysis, likewise failing to achieve convergence well before reaching a slip of 15 mm.

- Proposed hybrid model in this study: Achieved a deviation in load-carrying capacity between FE and experimental results of under 9%, with negligible scatter in the sensitivity analysis, while maintaining full and stable numerical convergence up to the complete 15 mm slip.

3.3. FAILURE MECHANISMS AND STRESS STATE ANALYSES

Inspection of the deformed specimens following the tests, alongside the analysis of von Mises stress contours in the FE model, revealed the specific characteristics of the failure mechanisms for individual components of the shear connector.

3.3.1. Bolt Behaviour and Observed Deviations from Eurocode 5

Across all tested series (S1, S2, and S3), the primary failure mechanism of the bolt is characterised by the formation of a single plastic hinge within the CLT panel.

Stress state analysis in the FE model revealed an important finding: during connection deformation under working load, a plastic hinge forms and the bolt head undergoes rotation. Consequently, the edge of the bolt head presses against the steel profile plate. This creates an eccentric contact and generates a significant local bending moment in the bolt shank in the immediate vicinity of the head (Figure 7).

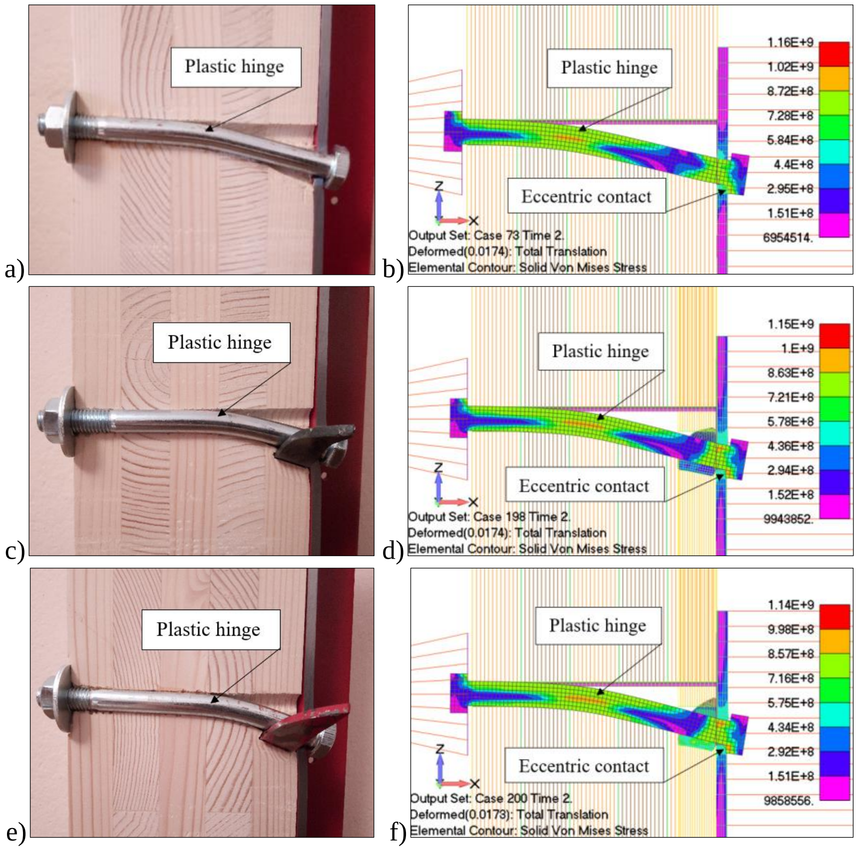


Figure 7: Failure modes of the shear connector – experiment and FE model: a,b) unreinforced, c,d) S235 reinforcing element, e,f) S275 reinforcing element

The observed phenomenon directly contradicts the simplified assumptions of Eurocode 5 [19], which stipulate that for thin plates (with a ratio of $t/d \leq 0.5$, where in this study $t/d = 4/10 = 0.4 < 0.5$), the bending moment near the bolt head can be completely neglected. The FE analysis clearly demonstrates that the combined action of this bending moment and the shear force in the bolt at the shear plane intersection induces partial yield of the cross-section, thereby altering the stress state throughout the entire shear connection.

3.3.2. Behaviour of the Reinforcing Element

The deformation mechanism of the reinforcing element is directly governed by the strength of the applied steel:

Series S2 (S235 Steel): Due to the lower strength of the steel, three plastic hinges form within the reinforcing element – one at the midpoint in the zone of direct contact with the bolt, and two at the quarter-points of its length. This three-hinge mechanism allows the element to "conform" to the groove, exerting continuous pressure on the timber fibres (Figure 8a,b).

Series S3 (S275 Steel): Due to the higher steel strength, only a single plastic hinge forms at the midpoint of the reinforcing element. The element depresses the lower edge of the groove at its midpoint, while its ends lift up and press against the upper edge of the groove in the CLT (Figure 8c,d).

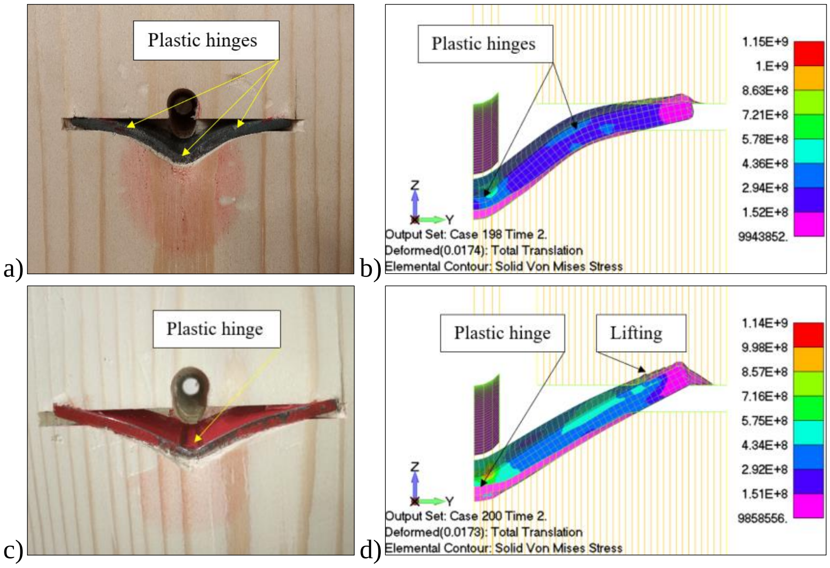


Figure 8: Failure modes of the steel reinforcing elements – experiment and FE model: a,b) S235 reinforcing element, c,d) S275 reinforcing element

4. CONCLUSIONS

Based on the experimental testing and nonlinear FE simulations of the novel reinforced dowel-type connection for steel–cross-laminated timber (CLT) composites, the following conclusions can be drawn:

- Significant improvement in mechanical performance: The incorporation of a steel reinforcing element into the CLT panel groove achieved an increase in load-carrying capacity and a substantial increase in the slip modulus compared to the standard unreinforced bolt.

- Preservation of the ductile failure mechanism: Despite the significant increase in stiffness, the connection maintained a highly ductile character, accommodating maximal joint slip without brittle splitting of the CLT, owing to the successive formation of plastic hinges in both the bolt and the reinforcing element.

- Exceptional efficiency of the hybrid timber FE model: The newly formulated hybrid approach (coupling ROD timber elements with PLATE contact shells) demonstrated excellent accuracy and complete numerical convergence up to a 15 mm slip, overcoming the chronic instability issues inherently present in continuum models from the literature.

- Reassessment of design standards (Eurocode 5): Deformation analysis of the experimental specimens and FE results demonstrated that the contact between the bolt head and the steel profile, with rope effect, generates a substantial local bending moment near the shear plane even for ratios of $t/d < 0.5$. This calls into question the justification for neglecting this effect within the design rules of EN 1995-1-1.

- Recommendations for practical application and material selection: Although the reinforcing element made of S235 steel exhibited a slightly higher connector load-carrying capacity, a higher strength grade steel (S275) is recommended for practical applications in steel-CLT composite structures. The use of S275 steel provides a higher initial slip modulus, bringing the actual behaviour of the shear connector closer to a theoretically ideal rigid-plastic constitutive model. Consequently, maximum stiffness is attained under Serviceability Limit State (SLS) loading – preventing excessive joint slip. At the same time, under Ultimate Limit State (ULS) deformations, the plasticization of the bolt and reinforcing element preserves high ductility and deformation capacity without the risk of brittle CLT failure.

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