

ENHANCING PUNCHING RESISTANCE OF CROSS-LAMINATED TIMBER PANELS WITH GLUED-IN STEEL PLATE REINFORCEMENT

Michal Kázsmér^{*1}

^{*} michal.kazsmer@stuba.sk

¹ Faculty of Civil Engineering STU in Bratislava, Radlinského 2766/11, 810 05 Bratislava

Abstract

This paper proposes an innovative solution for reinforcing cross-laminated timber (CLT) panels against punching effects using a glued-in steel plate. The steel column head is shaped as a six-pointed star, inserted into grooves in the CLT panel, and bonded with a two-component epoxy adhesive. A numerical model was developed to verify the potential reinforcing behaviour of the connector. The model was based on boundary conditions representing the set-up of a future experiment. This reinforcement reduces shear stress in the critical circumference and shifts it away from the support, thereby improving the punching resistance. Preliminary analysis suggests a possible 22% punching resistance increase.

Keywords

Cross-laminated timber (CLT); point support; concentrated load; punching shear reinforcement

1 INTRODUCTION

The scientific and engineering community has increasingly focused on achieving large-span, point-supported slabs, beginning in Switzerland in 2016 with Zöllig [1], who proposed slab spans of 8 m x 8 m with variable loads up to 5 kN/m². Two fundamental challenges associated with this type of construction had to be addressed to achieve this objective.

The first challenge is the development of moment-resisting or semi-rigid connections between CLT panels. A potential solution involves butt-jointed connections using polyurethane (PU) adhesive [1]; however, these joints show several weaknesses, as highlighted by Lei Zhang et al. [2]. The bending stiffness and resistance of these joints within CLT structures were investigated by Sigong Zhang [3], who demonstrated very low bending stiffness in various types of screwed connections. Current research on moment-resisting connections within CLT panels is underway in Canada at the University of British Columbia, although no results have been published yet.

The second challenge relates to the punching resistance of CLT panels. One of the first studies in this area was conducted by Mestek in 2011, examining the punching resistance of point-supported CLT panels both without reinforcement and with reinforcement using fully threaded screws [4], [5], Fig 1.

The first commercial product for reinforcing the area above the support was developed at the University of Innsbruck [6], [7], see Fig. 2. This product utilizes the principle of reinforcement with fully threaded screws. Muster investigated the effect of an opening (for column passage) on the bending resistance of a point-supported CLT panel and reinforcement through panel thickening above the support [8], see Fig 1.

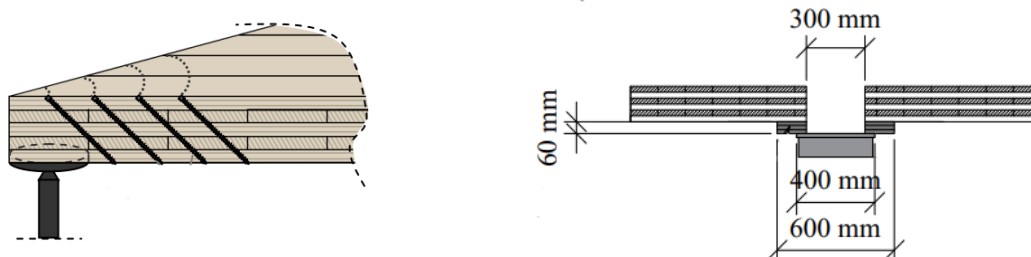


Fig. 1 Reinforcement of a point-supported slab using fully threaded screws (left) [4]; reinforcement using an embedded wood-based column head (right) [8].

Currently, the only commercial solution for reinforcing the area above the support involves a highly labour-intensive installation, requiring the application of at least 48 fully threaded screws on-site. This paper presents a new design to enhance the punching shear resistance of CLT panels using glued-in steel plates. The bonded plates could be fabricated in the workshop, significantly reducing on-site assembly time and making point-supported CLT slabs more attractive to assembly workers.

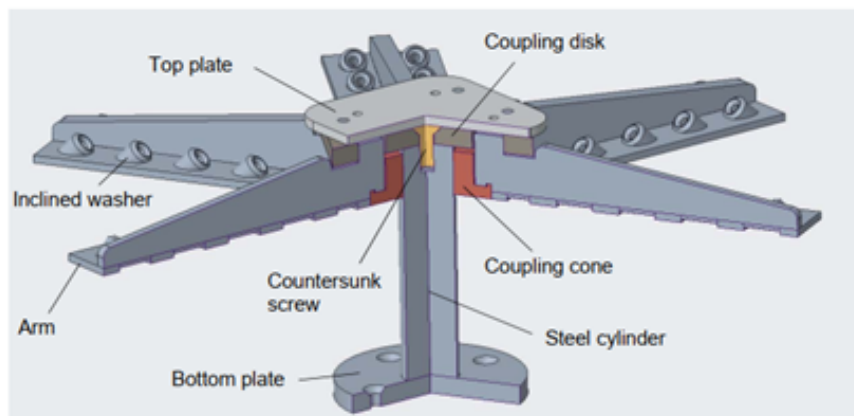


Fig. 2 Spider by Rothoblaas [7].

2 METHODOLOGY

Finite element method (FEM) model was developed, based on punching shear experiment performed by the Department of Concrete Structures and Bridges at the Central Laboratories of the Faculty of Civil Engineering, Slovak University of Technology in Bratislava. Similar experiments were conducted by Bolešová in 2022 [9] (see Fig. 3), among others. The boundary conditions were specifically established to align with laboratory constraints, as the experimental work is planned to be conducted there in the future. Similar experiments on CLT panels were also performed by Mestek [4], although with linear support, by Muster [8] using a vertically inverted setup, and by Bogensperger [10].

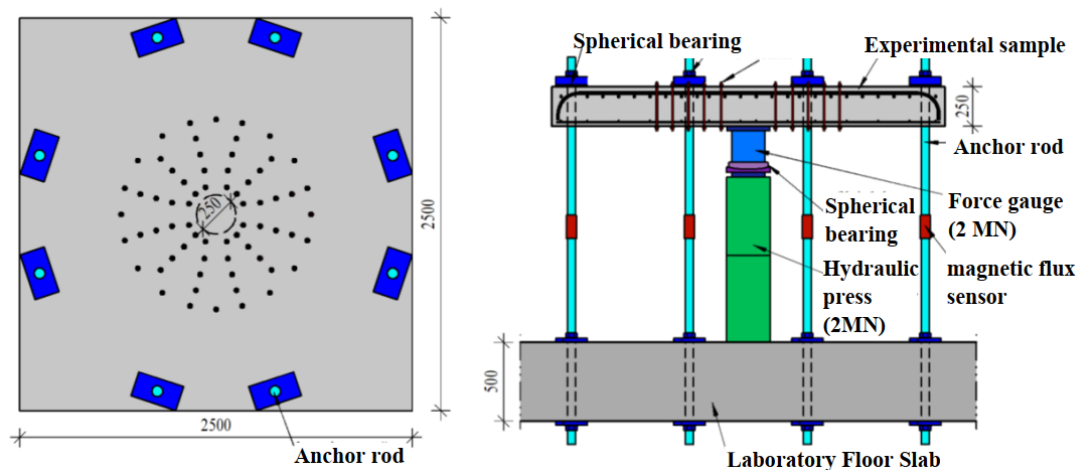


Fig. 3 Experimental setup according to Bolešová [9].

The experimental specimen Fig. 4, secured and supported within the testing setup, simulates a locally supported floor slab above an interior column with a span of approximately 5 to 6 metres. The specimen is supported along its perimeter at eight points using M32 anchor rods fixed into the floor. The anchor points on the floor are arranged in a regular grid with a spacing of approximately 750 mm. The anchoring of the rods above the top edge of the specimen is secured with nuts and washers with spherical bearings placed beneath.

The specimen is loaded with a steel plate with a diameter of 280 mm and a thickness of 25 mm, made of S355 grade steel. A load cell with a capacity of 2 MN anchored to the underside of the specimen, is positioned beneath the plate on a spherical bridge bearing. The slab loading is carried out using a hydraulic press placed under the bearing on a base to provide sufficient clearance beneath the floor slab.

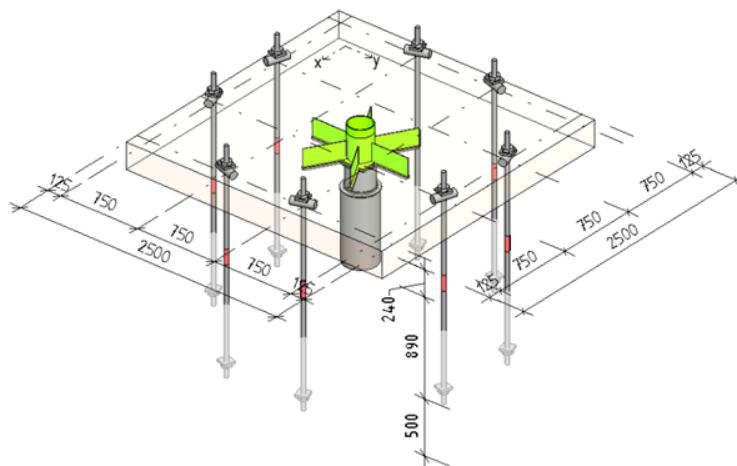


Fig. 4 Scheme of the experimental setup.

Three types of specimens were prepared, with each type consisting of four identical samples (a total of 12 specimens). The first type had no punching shear reinforcement and included an opening for a column with a diameter of 220 mm. The second type was reinforced with a glued-in steel head, as described in the following chapters, without any perforation. The third type featured a perforated glued-in steel head.

The force applied by the hydraulic press was monitored using a load cell during the loading of all specimens. Magnetic flux monitoring devices was placed on all anchor rods to determine the distribution of forces within the slab among the individual rods. Eight strain gauges were positioned on the top surface around the column (four in each direction) to measure the strain in the outermost lamella of the CLT in tension. Spirit levels were installed along the four edges of the slab to measure the specimen's rotation.

Additionally, the vertical displacement of the panel was measured using LVDT displacement sensors. These sensors were arranged in a cross pattern, extending from the column face to the edge of the specimen. Four LVDT sensors were positioned, totalling eight sensors in each direction.

CLT PANEL

A 7-layer panel with overall dimensions of 2.5 x 2.5 m and a thickness of 240 mm was selected. The configuration of the individual layers was 30-40-30-40-30-40-30 mm. The timber used in the panel met a minimum strength class of C24 according to EN 338. The cross-sectional characteristics are summarized in Tab. 1.

Tab. 1 Moments of inertia for the CLT L7 30-40-30-40-30-40-30.

Moment of inertia about the Y-axis	$I_{y,net}$	$74.4 \cdot 10^7$	mm ⁴
Moment of inertia about the Z-axis	$I_{z,net}$	$40.8 \cdot 10^7$	mm ⁴

ADHESIVES

Given the advanced stage of research and standardisation of glued-in rod (Bonded in Rods) connections in timber structures, as demonstrated by authors such as Tannert [11] and Duchoň [12], the use of adhesives was prescribed in the new generation of Eurocode 5. The mechanical property requirements for two-component epoxy and polyurethane adhesives are defined in the EN 17334:2021 standard.

The German technical regulation *Allgemeine bauaufsichtliche Zulassung/Allgemeine Bauartgenehmigung Nr. Z-9.1-770*, issued by DIBt (Deutsches Institut für Bautechnik) [13], outlines the technical requirements, production processes, and construction provisions necessary to provide safe and efficient use of glued-in perforated plates in construction. It prescribes the use of the two-component epoxy adhesive WEVO-Spezialharz EP 32 S with the hardening accelerator WEVO B 22 TS.

The use of adhesives is also defined by manufacturers in their technological guidelines, such as the XPEPOX product from Rothoblaas [14]. The selected adhesive for the experiment was the two-component epoxy adhesive XPEPOX from Rothoblaas. The strength characteristics of this adhesive are shown in Tab. 2. The *L* (liquid) version was used, and it is recommended for filling high vertical joints up to 2 mm thick [14].

Tab. 2 Material characteristics for XEPOX od Rothoblaas [14].

Axial tensile strength (adhesive)	27	MPa
Shear strength (adhesive)	27	MPa
Compressive strength	88	MPa
Tensile strength	36	MPa
Shear strength	28	MPa
Tensile modulus of elasticity	4600	MPa
Compressive modulus of elasticity	3098	MPa

BONDED-IN-TEEL COLUMN HEAD

This component consists of a steel cylinder with an external diameter of 216 mm and a wall thickness of 8 mm, extending 50 mm above the CLT panel surface. The extension is intended to facilitate a potential connection with the column base from the floor above the panel (see Fig. 5).

The head is capped with an end plate at the column interface (in this case, at the hydraulic press) measuring 280 x 80 mm and 20 mm thick. This provides even distribution of contact stress at the top edge of the column. The plate's footprint is reduced by 20 mm relative to the column cross-section to provide coverage of the steel head beneath the timber surfaces, enhancing fire resistance.

The arms are 160 mm in height, 357 mm in length, and made from 10 mm thick steel plates. The arms do not extend across the entire height of the CLT panel. The top two layers of the panel remain intact to provide the biaxial transmission of tensile stresses from the negative moment over the support through the CLT cross-section. This prevents potential brittle failures at the wood-adhesive-steel interface. The head contains six arms arranged

radially with a spacing of 60° . The head is always oriented so that four arms align with the direction of the expected higher load. In the case of a symmetrical plan layout, the four arms are oriented parallel to the surface lamellae.

The lower flange of the head's arms is 8 mm thick and 50 mm wide. All steel components are made from S355-grade steel.

The arms can be fabricated in two variants: with perforation and without. The advantage of non-perforated arms is that their cross-section remains unweakened. However, this design is more labour-intensive, requiring sandblasting to class SA2.5/SA3, followed by coating with an adhesive primer according to the manufacturer's specifications.

Each arm contains a total of 65 holes with a diameter of 10 mm and a centre-to-centre spacing of 16 mm for the perforated variant. In this case, the head is easier to manufacture, but the overall connection resistance is reduced.

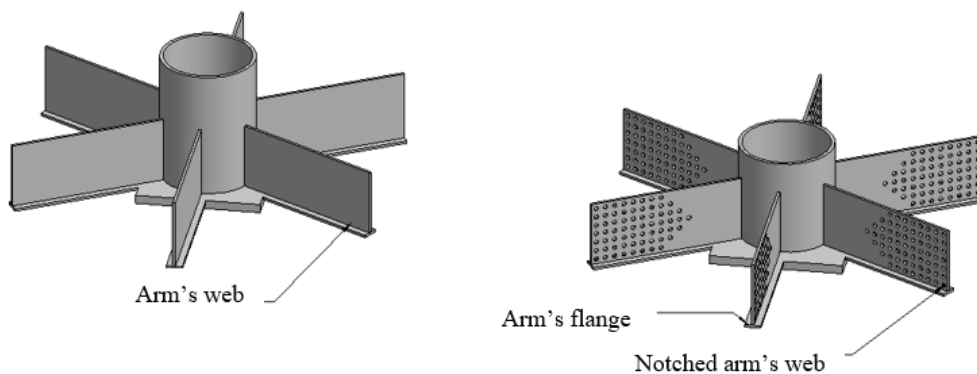


Fig. 5 Alternative designs of the steel column head.

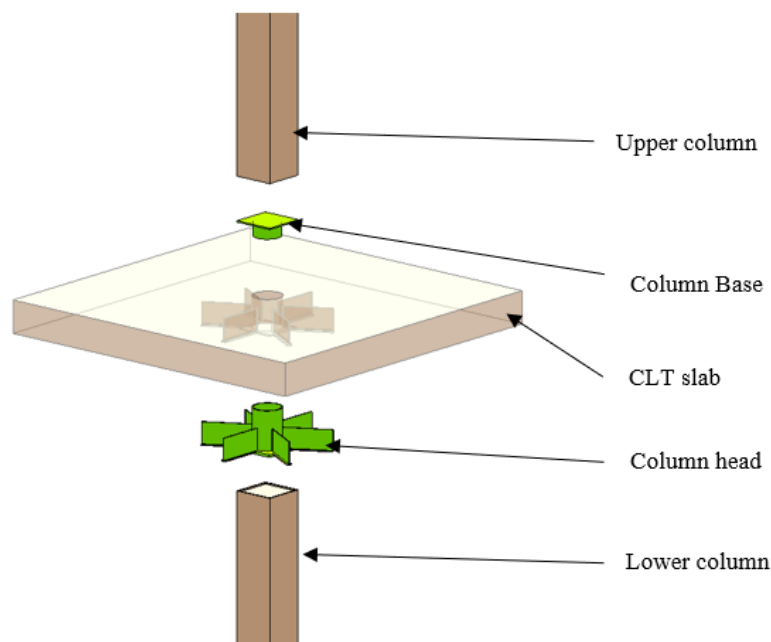


Fig. 6 Scheme of the steel column head application.

3 RESULTS

RESISTANCE OF THE UNREINFORCED SLAB

The resistance of the unreinforced slab was determined based on a publication comparing various calculation approaches for point-supported slabs [15] equation (1). The mean value derived from the calculations was established at $F = 471.91$ kN, corresponding to the force applied by the hydraulic press at which specimen failure occurs. The failure mode is expected to be rolling shear in the principal load-bearing direction of the panel. The stress state at the force F_{mean} is illustrated in the Fig. 7.

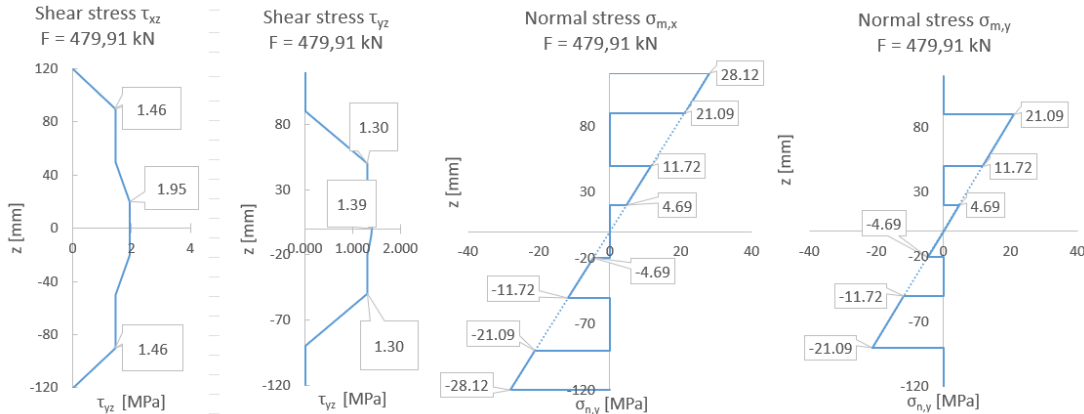


Fig. 7 Stress distribution in the cross-section at force $F = 479.91$ kN.

$$\tau_{iz} = \frac{V_{iz} \cdot S_{iy}}{I_{iy} \cdot b(z)} \quad (1)$$

Where τ_{iz} is the shear stress in kPa, V_{iz} is the shear force in kN, S_{iy} is the static moment in m³, I_{iy} is the moment of inertia in m⁴, $b(z)$ is the effective width in m.

The rolling shear strength of the panel is considered to be $f_{\text{mean}} = 1.6$ MPa, increased by a factor of $k_{r,pu} = 1.2$, as per Muster [8].

RESISTANCE OF THE REINFORCED SLAB

The slab with reinforcement was considered in the following configuration: a sandblasted steel head with a lower flange of 8 mm thickness and 50 mm width, as shown in Fig. 6. The computational model was created based on the geometry of the assembly and the components used. To account for the characteristics of the CLT panel, a layered material model was applied, reflecting the properties of the CLT panel. CLT was supported at 8 anchor points with pinned support. FE model was loaded at the base plate of the column head with force $F_{\text{reinforced}}$.

The steel head was modelled using shell elements, corresponding to the actual dimensions and material properties of the component. The connection between the CLT panel and the steel head was defined as rigid, capturing all translations and rotations. The bedding of CLT on contact with steel column head was accounted for with spring elements.

The quadrilateral mesh was chosen with a mesh size of 100 mm with refinement at corners and edges of 70 %. Nonlinear analysis was performed, with CLT being linearly elastic material and steel with non-linear material (trilinear) work law.

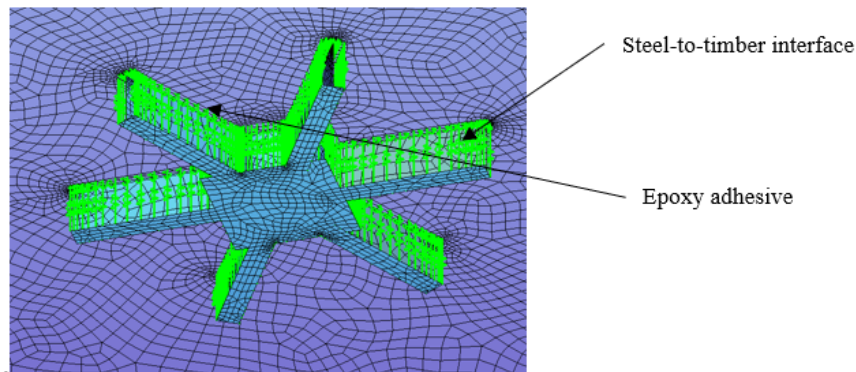


Fig. 8 Shell element FEM model.

The arms of the glued-in steel head transfer a portion of the transverse forces from the slab directly to the support. This can be observed in the reduction of shear forces along the original shear perimeter by approximately half, as shown in **Fig. 9** and **Fig. 8**. It can also be assumed that the actual critical perimeter shifts beyond the boundary of the glued-in head. The critical perimeter at this new location would reach a total length of **2.766 m** instead of the original **1.792 m**, significantly increasing the punching shear resistance.

Such an increase in punching resistance results in expecting that the governing failure mode will no longer be the shear failure of the CLT panel but rather the failure of the upper tensioned layers of the CLT panel due to bending moments. Assuming a mean tensile strength of the timber $f_{m,mean} = 34.0 \text{ MPa}$, the specimen is expected to fail at a force of $F_{reinforced} = 580.27 \text{ kN}$ in the hydraulic press.

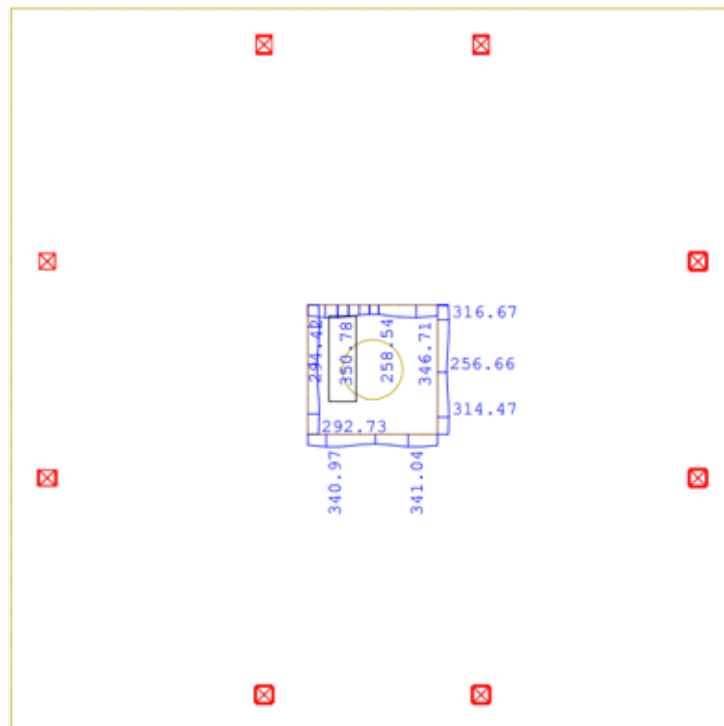


Fig. 9 Shear forces in the slab along the critical perimeter at force F .

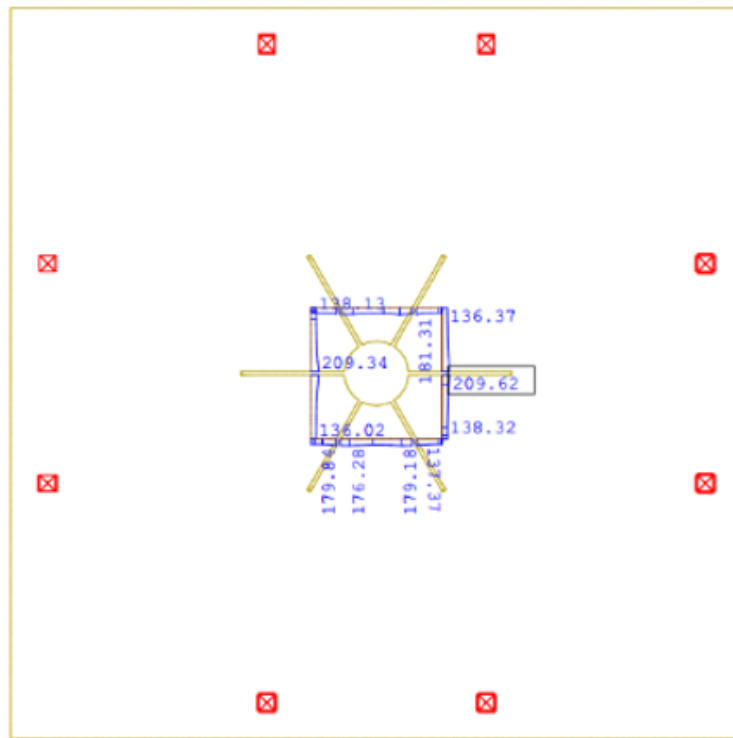


Fig. 10 Shear forces in the slab along the critical perimeter at force $F_{reinforced}$.

4 DISCUSSION

The analytical model used in this study has its limitations. These limitations are specifically:

- The necessity of analytically segmenting the CLT panel at the insertion point of the head represents a full-depth cut through the panel.
- Force distribution into the head arms only at the intersection of the CLT panel's mid-plane and the mid-plane of the arm.
- CLT was modelled using a linear-elastic material, therefore cannot describe the formation of cracks and their influence on the overall stiffness of the panel.

It can be concluded, based on these limitations, that the analysis correctly describes the global actions on the steel column head; however due to the modelling of CLT (only as a 2D layered element) the load actions on CLT, and a glued interface, cannot be read accurately.

The reduction of shear force in the original critical perimeter is evident due to the bending stiffness of the glued-in column head, rigidly connected to CLT. The column head extends the supported area and therefore pushes the critical circumference outwards; however the shape of the critical circumference is unclear (hexagonal, circular or rectangular).

5 CONCLUSION

This connector introduces new possibilities for resolving the transfer of a column through point-supported CLT panels, while also increasing its resistance in punching shear. The connector could be assembled and inserted in CLT slabs in the workshop which would significantly improve on-site assembly. Fire resistance is accounted for since all surfaces of steel can be covered by a layer of timber. However, glueing the column head into CLT could be difficult due to its shape, also the current trend is reducing the use of adhesives.

Preliminary analysis has shown that glued-in plates can represent an effective method for reinforcing the critical area above the support of point-supported CLT panels against punching shear. Simplified analysis suggests that it may be possible to achieve up to 1.22 times the reinforcement of the panel, with a shift in the dominant failure mode to the rupture of the tensioned layers of the CLT panel due to bending, if no failure occurs in the adhesive. Structural design, such as the lower flange of the arms or the reduction of arm height to avoid critical tensioned lamellae are designed to minimize adhesive stress and prevent brittle failures, as observed and studied in [2].

However, this study is limited by a simplified computational model. The issue is highly complex, and accurate consideration of force distribution into the head arms and stress at the timber-adhesive-steel interface requires the creation of a FEM model using 3D solid elements.

References

- [1] ZÖLLIG, Stefan et al.: Timber Structures 3.0 – New Technology For Multiaxial, Slim, High Performance Timber Structures. In Proceedings of the WCTE 2016: World Conference on Timber Engineering. 22/08/2016-25/08/2016, Wien, Austria. TU Wien, 2016, pp. 1258–1266. ISBN 978-3-903039-00-1.
- [2] ZHANG, Lei et al.: Robustness Of Adhesively Bonded Panel-To-Panel. In Proceedings of the WCTE 2023: World Conference on Timber Engineering. 19/06/2023-22/06/2023, Oslo, Norway. Norwegian University of Science and Technology (NTNU), 2023, pp. 1160-1167. ISBN 978-3-903039-00-1.
- [3] ZHANG, Sigong et al.: Characterizing flexural behaviour of panel-to-panel connections in cross-laminated timber floor systems. Structures. 2020, vol. 28, pp. 2047-2055. ISSN 2352-0124. <https://doi.org/10.1016/j.istruc.2020.10.040>
- [4] MESTEK, Peter. et al.: Design concept for CLT -reinforced with self-tapping screws. In proceedings of the Focus Solid Timber Solutions - European Conference on Cross Laminated Timber. 21/05/2013-22/05/2013 Graz, Austria, 2013, ISBN 978-1-85790-181-8
- [5] MESTEK, Peter. Punktgestützte Flächentragwerke aus Brettsperrholz (BSP) – Schubbemessung unter Berücksichtigung von Schubverstärkungen [online]. München, 2011. Dissertation thesis. Technischen Universität München. Fakultät für Bauingenieur- und Vermessungswesen. Available at: <https://mediatum.ub.tum.de/?id=1079875>
- [6] Maurer, B., Maderebner, R.: Cross Laminated Timber under Concentrated Compression Loads - Methods of Reinforcement. Engineering Structures. 2021, Volume 245, pp. 0141-0296. ISSN 0141-0296 <https://doi.org/10.1016/j.engstruct.2021.112534>
- [7] ETA-19/0700, SPIDER Connector and PILLAR Connector: Rotho Blaas s.r.l, Österreichisches " Institut für Bautechnik, Wien, 2020.
- [8] MUSTER, Marcel. Column-Slab Connection In Timber Flat Slabs [online]. Zurich, 2020 Dissertation thesis. ETH Zurich. Available at: <https://www.research-collection.ethz.ch/handle/20.500.11850/461541>
- [9] BOLEŠOVÁ, Mária. Vplyv História Zaťažovania Na Účinnosť Zosilnenia Lokálne Podopretej Stropnej Dosky Dodatočne Vloženou Šmykovou Výstužou. Dissertation thesis. Bratislava, 2022. Slovenská Technická Univerzita v Bratislave, Katedra betonových konštrukcií a mostov.
- [10] BOGENSPERGER, Thomas. et al.: Concentrated load introduction in CLT elements perpendicular to plane – experimental and numerical investigations. In Proceedings of the WCTE 2016: World Conference on Timber Engineering. 22/08/2016-25/08/2016, Wien, Austria. TU Wien, 2016, pp. 1258 -1266. ISBN 978-3-903039-00-1.
- [11] AYANSOLA, Gbenga. et al.: Glued-in multiple steel rod connections in cross-laminated timber. The Journal of Adhesion. 2020, Volume 98(6), pp. 810-826. <https://doi.org/10.1080/00218464.2021.1962715>
- [12] DUCHOŇ, Vladimír.: Teoretická a Experimentálna Analýza Spojov s Vlepovanými Tyčami. Dissertation thesis. Bratislava, Slovakia, 2016. Slovenská Technická Univerzita v Bratislave.
- [13] Deutsches Institut für Bautechnik (DIBt). Allgemeine bauaufsichtliche Zulassung/Allgemeine Bauartgenehmigung Nr. Z-9.1-770. Berlin: Deutsches Institut für Bautechnik, 2020.
- [14] Technical data sheet by Rothoblaas [product catalogue] XEPOX L – Liquid, two-component epoxy adhesive. [Accessed 06/01/2025]. Available at: <https://www.rothoblaas.com/products/fastening/xepox-epoxy-adhesive/xepox-l-liquid>
- [15] KÁZSMÉR, M.: Slab-Column Connection of Cross-Laminated Timber for Punching: Comparison of Current Simplified Methods. In proceedings of the Juniorstav 2024, 26th International Scientific Conference Of Civil Engineering, pp. 1-9. Brno, Czechia, VUT v Brne, 2024, ISBN 978-80-86433-83-7. Available at: <https://doi.org/10.13164/juniorstav.2024.24093>