EXPERIMENTAL VERIFICATION OF CEILING JOINT PERFORMANCE IN CLT-STEEL HYBRID STRUCTURES

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Abstract
In the research for sustainable hybrid structures, cross-laminated timber (CLT)-steel structures have gained widespread popularity and become a widely used engineered solution. This paper points out the unused potential of CLT-steel hybrid ceiling systems, focusing on creating the effect of a continuous deck. The study aims to create a connection capable of interconnecting panels through a hidden beam. The essence is to prevent the decks from rotating at the point of support, thus reducing overall slab deflection. Following the initial adjustment of the proportions of the connection, it is possible to state that the assumptions have been met. The results from the numerical analyses present two variants of the connection, which can be further subjected to experimental analyses.

Keywords
CLT, DELTABEAM, hybrid structures, numerical analyses, experimental analyses

1 INTRODUCTION

Timber-steel hybrid structures are experiencing a surge in popularity and usage: the combination of mass timber slabs and steel frame merges the advantages of both materials, offering an effective solution for the increasing requirement for sustainable construction. This innovative blend combines both, the robustness of steel and the natural sustainability of timber [1] creating a harmonious combination. The use of CLT as a substitute for mass timber slabs has emerged as a popular choice in this hybrid model [2]. CLT, with its exceptional strength and versatility, offers an eco-friendly alternative to conventional building materials while maintaining structural integrity [3]. This paper presents the expanding trend, which can achieve similar results, while reducing the carbon footprint compared to conventional designs [4].

SPECIFICATION OF HYBRID CEILING STURCTURE AND THE CONNECTION

With the aim of achieving superior parameters compared to conventional load-bearing systems, it is necessary to assemble the most effective modules of individual components within the system. This is accomplished by positioning the ceiling panels on the lower flange of the beam, which enables a significantly thinner construction (Fig. 1). The panels are placed on the lower flanges of the beams, thereby reducing the overall height of the ceiling structure, and creating what is known as a Slim-Floor [5].

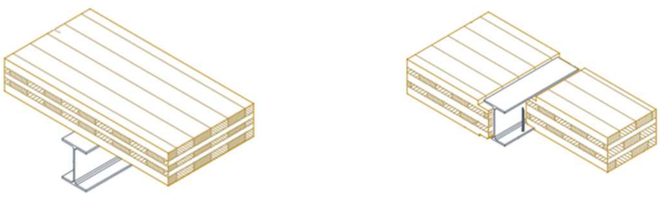

Fig. 1 Examples of concepts of assembling hybrid ceiling structure and slim-floor hybrid structure [2].

The load transfer mechanism’s essence, in connecting CLT ceiling panels to the DELTABEAM (DB), is fundamentally based on the transfer through a compression arch located within the negative bending moment region for multi-span ceiling panels. In this arrangement, forces are transferred by the principle of the arch effect

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by creating wedged ceiling panels pushing through the concrete fill towards the walls of the beam (Fig. 2). The beam and the gap between the bevelled edge of the panel and the wall of the beam are filled with concrete [6]. The reinforcement passing transversely through the beam is positioned so that a tensile effect is induced in the reinforcement, i.e., closer to the upper edge. The rods pass through additional holes at the upper part of the beam. Further, the reinforcement passes into the CLT panel, where it is embedded in a milled groove, which is subsequently infilled with concrete. The paper examines the appropriateness of the groove shape and its capacity to prevent deformation of the slab in the negative bending moment region.

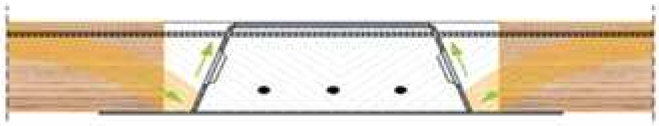

Fig. 2 Load transfer [7]

The samples are assembled using suitable materials, optimizing the arrangement to maximize the load-bearing capacity of the connection [7].

Several findings and their connections to the current research area were identified from the previous research carried out by Peikko (Fig. 3). As part of the experimental analyses, three basic groups of samples were compiled. The ongoing research will focus on the first series (type A). In this series, the specimen consisted of a two-span continuous ceiling utilizing CLT boards, supported by DELTABEAM beam at the point of support. The ceiling panels were connected to each other through the beam with reinforcement. The rods were installed in the grooves of the CLT panels which were both, interconnected using concrete, and also connected with the beam. The research aimed to verify the behaviour of the entire ceiling system as a cohesive unit. The analyses showed that the construction forming the same angle of the edge of the CLT panel, and the wall of the beam had a beneficial effect (Fig. 2), which was further investigated in the current research. These analyses also concluded that the transverse reinforcement created a mutual connection between the ceiling slabs through the beam, but this potential has not been explored in the research [7].

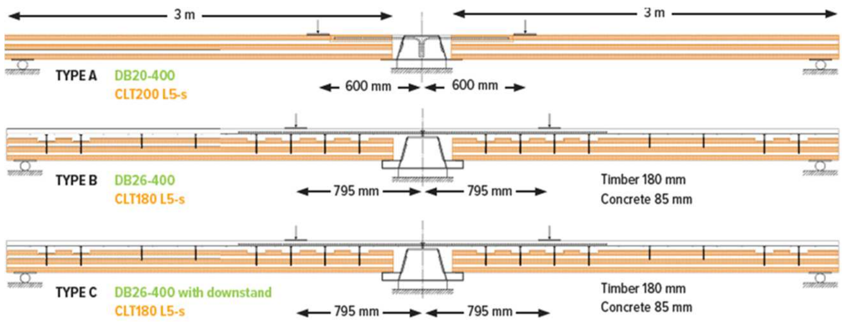

Fig. 3 Overview of specimens [7].

It is assumed that by interconnecting the panels, the rotation of the slab in the area above the support is prevented to a certain extent. Thus, it is possible to state that it is a semi-rigid connection.

2 METHODOLOGY

Numerical analyses

Numerical analyses were predicated on the development of Finite Element Method (FEM) models, which accurately reflect the boundary conditions corresponding to actual samples (Fig. 4 and 5). These models were subsequently constructed for laboratory verification.

Within the scope of these numerical models, material properties, inclusive of the orthogonal anisotropy of the wood, were considered. The fiber orientation was customized for each layer of the CLT panels. Each individual element consists of specific materials, CLT (C 24), concrete (C 20/25), DB (S 355), and rods (B 500 B). The cohesion between individual layers and materials was also accounted for via the coefficient of friction suitable for the given combination of materials. The procedure for loading the sample is comparable to the load on the original structure. The load symbolizes the surface weight applied on the ceiling slabs.

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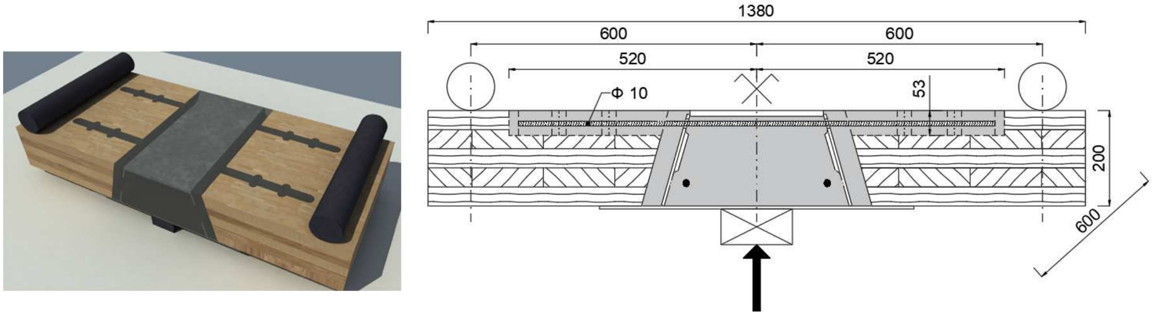

Fig. 4 Test set-up of sample A.

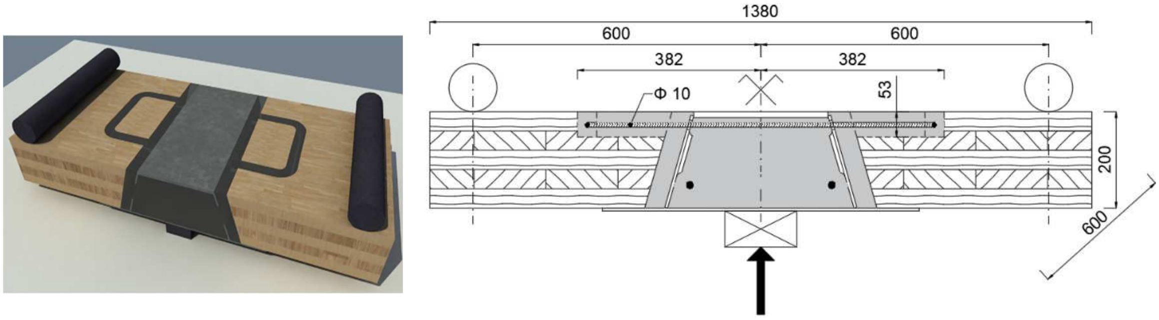

Fig. 5 Test set-up of sample B.

An integral component of the numerical analyses was the evaluation of Sample A (Fig. 6), which was subsequently followed by a comprehensive examination of Sample B.

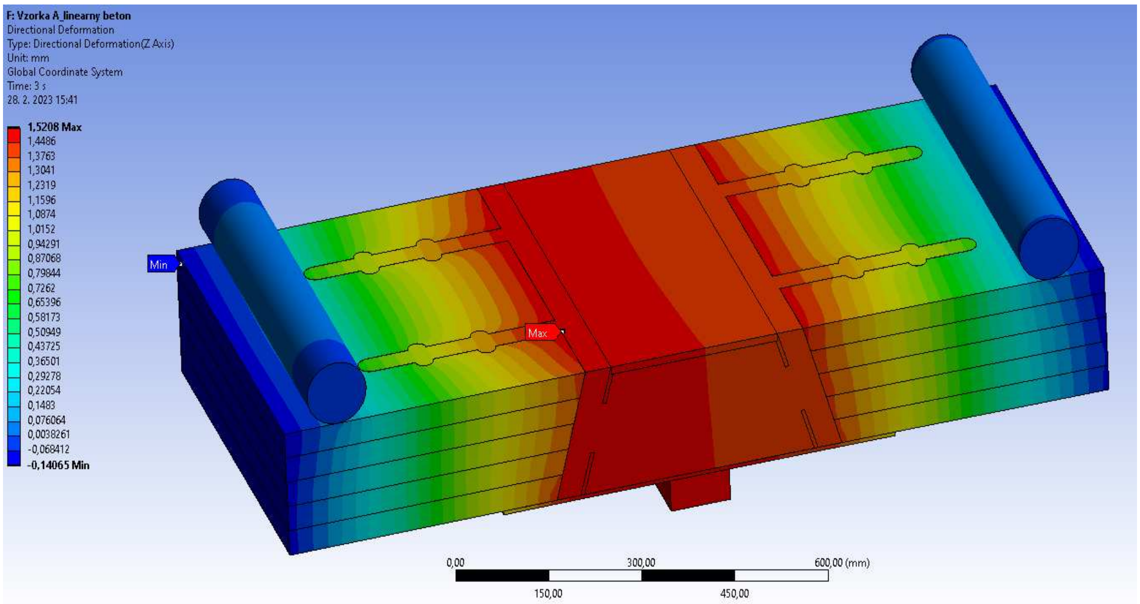

Fig. 6 Vertical deformation of specimen A.

There is an apparent asymmetry in the deformations caused by the way the structure is supported. This asymmetry arises from the use of cylinders for support. One support can only rotate around its axis, while the other support is capable of both rotation as well as horizontal shifting.

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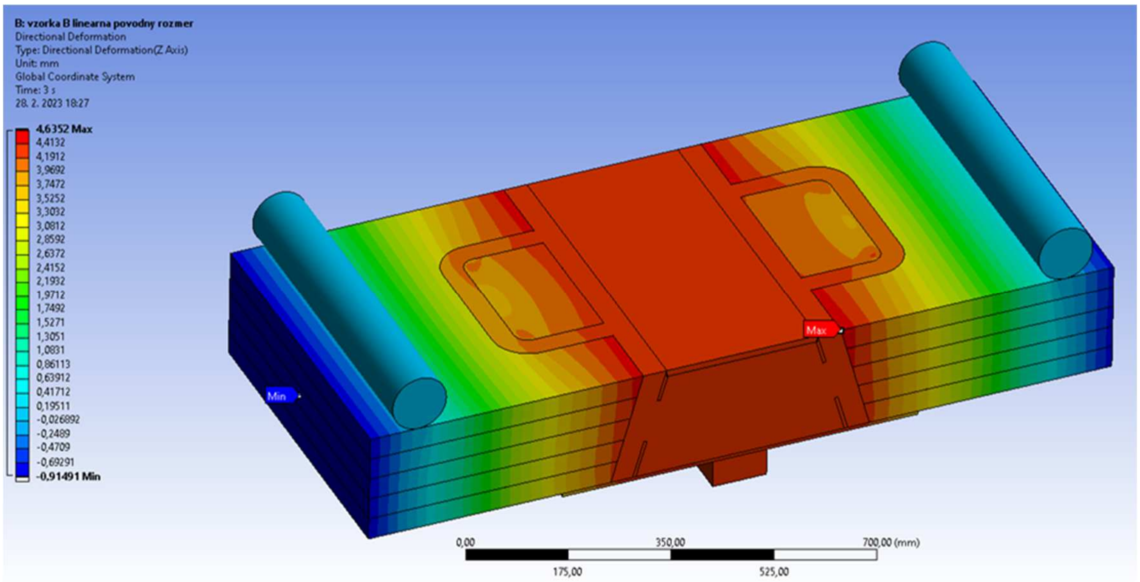

Fig. 7 Vertical deformation of specimen B1.

The numerical investigation substantiated the necessity of positioning the reinforcement up to the boundary of the shear flow area, passing from the slab to the beam. In Specimen B1, where the reinforcement is positioned at the minimum distance from the edge of the CLT panel, it is evident the influence of reinforcement length (Fig. 7). This contrasts with Specimen B2 (Fig. 8), where the U-shaped reinforcement extends to the boundary of the shear flow area (compression diagonal ending from edge of support).

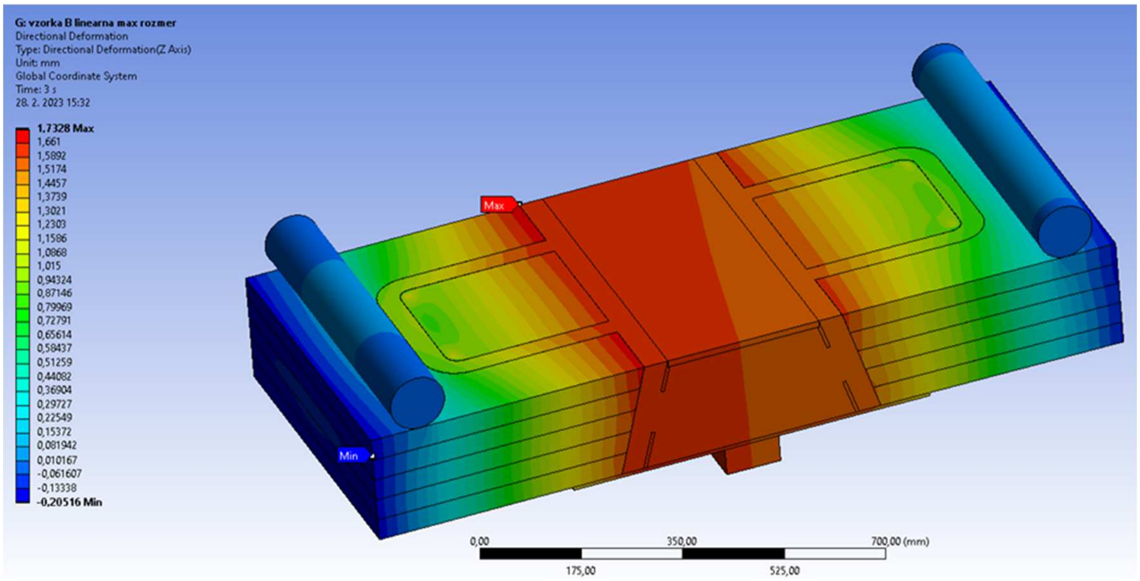

Fig. 8 Vertical deformation of sample B2.

By encompassing the entire shear zone, deformations are reduced, a phenomenon also observed in Sample A. Under identical load conditions, a noteworthy reduction in vertical displacement by 2.902 mm is observed. The most significant finding is that, when the reinforcement length is maximized, there is a more significant activation of the CLT panels, and an improved connection occurs in the negative bending moment region.

Numerical analyses were used to verify the behaviour of the examined sample, and based on the obtained knowledge, it is now possible to focus on experimental analysis with additional knowledge.

Experimental analyses

The constructed samples are in compliance with the proportions set from the numerical analyses. An alteration in the class of concrete from C 20/25 to C 16/20 was assigned, while other elements remained unchanged regarding material grade. Prior to the concreting process, it was necessary to address the assumption that (related to the size of the sample), the specimen would be exposed to a higher degree of concrete shrinkage than what would typically occur on a construction site with larger volumes of materials (both concrete and timber). Consequently, an adhesion bridge was established. A universal adhesive was utilized, which was applied to all timber edges, where subsequent contact with concrete occurred. The principle was to apply wet concrete to even wet glue. Following the prescribed concrete hardening time, excessive shrinkage cracks were not observed on the structures.

Fig. 29 Set-up of specimen A.

After the stipulated 28-day period, Specimen A was positioned in the testing machine in accordance with the loading schemes (Fig. 9). In accordance with the press construction, the reverse-rotating specimen was installed. The methodology for both supporting and loading the specimen through the press aligns with the original proposal. The load was directed into the sample through the press, in the neutral axis of the lower flange of the DELTABEAM (Fig. 4).

3 RESULTS

As the applied force intensifies, deformations increase. This allows for the observation of a gap between the edge of the CLT panel and the concrete layer situated between the DELTABEAM wall and the CLT panel. Deformations on Sample A were measured using measuring needles, and both horizontal and vertical deformations on individual segments within the sample were monitored.

Fig. 30 Failure of specimen A.

When the force in the hydraulic press reached the maximum force applied in the ANSYS program on Sample A, a vertical deformation in the neutral axis of the beam of 6.40 mm was measured (Fig. 10). This represented an increase of 4.95 mm (1.45 mm) compared to the program. Upon reaching the maximum force in the press, a deformation of 7.48 mm was observed. Regarding vertical deformations (Fig. 11), the lifting up of the concrete block from the groove was also recorded at a value equivalent to max. load value from Ansys (64.86 kN), resulting in a lift of 0.43 mm compared to the numerical model of 0.33 mm. When reaching maximum force in the press (74.4 kN), the block was raised above the panel level by 0.52 mm.

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Fig. 41 Crack pattern development in groove.

The deviation of the CLT panel from the beam was recorded by detecting horizontal deformation (Fig. 10). At a force of 64.86 kN, a deformation of 1.56 mm was recorded, and under the same load in the numerical model, a gap of 0.25 mm was observed. At the maximum force in the press of 74.4 kN, the value of deformation was 1.9 mm. However, due to the plasticization of the reinforcement, a significant increase in values up to 29.78 mm was observed. It is necessary to consider the inclination of the CLT panel to which the measuring needle was attached and thus account for a certain degree of distortion in value.

Concrete damage can be observed on the structure in the area of the grooves in front of the expanded block (Fig. 12). Concrete deflection also occurred on the edge of the CLT panel and the concrete block adjacent to the beam wall. Due to excessive deformation, the reinforcement was pushed up to the edge of the CLT panel at the bottom ending of the groove. Bending of the lower flange was also observed. During measurement, it was possible to hear regular sounds indicating damage to the ribs on the reinforcement.

Fig. 52 Failure modes in specimen: cracking of concrete, fell out concrete, disclosure of rod.

It can be concluded that the structure successfully resisted the proposed and assumed load values and even after reaching maximum values of pressure, there was no total failure of the structure. The specimen withstood a force of 74.4 kN and subsequently excessive plasticization of the reinforcement occurred, leading to excessive deformations of the structure.

4 DISCUSION

In comparison to the research conducted by Peikko, a comparable failure of the concrete blocks was observed in the grooves where the cracks occurred. It can be inferred that in their case, there was also an infringement of the CLT panel as a result of rolling shear. This deviation is likely caused by the cut-out area created when the specimens were reduced, thereby eliminating excessive values causing rolling shear and especially no bending of the panel itself, as in the case of the research conducted by Peikko, where the panel spanned the entire span of one field on each side of the examined beam.

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Numerical analyses yielded different results from experimental measurements. Numerical models can be compared with each other, as they are based on identical boundary conditions and the models were set up in a similar manner. Based on this assumption, individual variant solutions were evaluated, which led to adjustments in the proportions for Sample B. The necessity to place rods up to the border of the shear flow area was discovered, which was also observable when comparing the deformation on the numerical models for Sample B1 and Sample B2.

As part of the experimental analysis (Sample A), the statement of functionality of the connection design was confirmed and the structure was able to withstand the proposed stress without failure.

Experimental analyses confirmed the assumption of failure within the connection. Despite differences compared to numerical models, the connection failed precisely due to failure of reinforcement when limit tensile stresses in cross-section of the rod were reached. The mechanism of gradual weakening of the concrete block and pattern of cracks was also observable. Cracks occurred identically in the numerical model for Sample A, as well as in the experimental specimen (Sample A). In the initial phase, a crack of the concrete block appeared before the first widening of the groove (in the direction from the beam) and subsequently before the second widening of the groove.

The connection concept and the potential for reducing deformation in the negative bending moment region are significant. In the near future, it will be necessary to perform a detailed analysis of the results from the experimental measurements and subsequently back-check the numerical models based on the data obtained during experimental measurements. Following this, the rotational capacity of individual connection variants will be estimated through the adjustment of the springs in numerical models, taking into account the deformations measured during experimental measurements.

5 CONCLUSION

Hybrid systems of ceiling structures introduce new possibilities in the field of structural design. The increasing trend of integrating solid timber ceiling panels with a steel frame has demonstrated the potential to achieve results overcoming the boundaries of traditional designs while significantly reducing the carbon footprint.

The research conducted provides certain assumptions that require further experimental analyses for accurate interpretation and a comprehensive understanding of the actual contribution of the researched area. The current research suggests that the mutual connection of ceiling slabs could be advantageous, highlighting the need for continued exploration in this field.

Moreover, this research has clarified the use of timber-steel hybrid structures in ceiling design and has identified several aspects that require further investigation. The main aspects include the groove shape and its capacity to prevent deformation of the slab in the negative bending moment region, as well as the load transfer mechanism within the connection of CLT panels to the DELTABEAM. The findings from this study contribute to the growing body of knowledge in this field and pave the way for future research. The overall goal is to optimize the design and performance of these structures and to achieve a more sustainable and efficient structural design.

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