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BONDING OF TIMBER AND HIGH-PERFORMANCE CONCRETE

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Abstract. Timber-concrete composite systems have emerged as a promising building technique, leveraging the strengths of both materials to improve load capacity, stiffness, and overall performance. In the presented study, high-performance concrete with perfect mechanical performance and durability is used in timber-concrete composite systems to further reduce the environmental footprint and optimize structural efficiency. The weakest point in general of these constructions is the interface between the concrete material and the wood. The focus in this study is on shear strength, specifically examining the combination of adhesive bonding with notch shear connections. Experimental results, by a push-off test, reveal that the inclusion of shear connectors is essential for effective and secure bonding, with adhesive application methods significantly influencing shear strength. The findings highlight the potential of timber-concrete composite systems high-performance concrete to achieve high shear strength and structural integrity through optimized adhesive and rib configurations. The goal is to make maximum use of the material's mechanical potential and significantly reduce the primary sources of raw materials. The presented article is based on the diploma thesis of Nick Vanheeswijck.

Keywords: High-performance concrete, timber concrete bonding, timber concrete contact, push-of test.

1. Introduction

The predominant use of concrete as a primary building material has long been established thanks to the variability of shapes, simple technology, and favourable price. In the construction sector, it is common to use solid concrete slabs. However, inherent limitations, such as low tensile capacity, require the incorporation of steel and other reinforcements into the tension zone. Tensile cracking in concrete slabs not only compromises structural integrity but also exposes steel reinforcement to moisture, contributing to corrosion and subsequent spalling [1] and contributes significantly to carbon emissions [2]. Timber floors offer a sustainable and environmentally friendly building option due to timber's recyclability, reusability, and sustainability. But also timber floors may face challenges such as excessive vibrations [3], fire resistance, and acoustic problems. In response to these challenges, there has been a growing interest in alternative building solutions that prioritise ecological sustainability in combination with structural efficiency. One such solution is the integration of timber into traditional concrete structures, forming Timber-Concrete Composite (TCC) systems. TCC systems capitalize on the properties of timber and concrete, offering a more efficient structural solution compared to conventional concrete-only or timber-only structures. The composite action of TCC systems distributes forces such that concrete experiences predominantly compression stresses while timber bears tension stresses, optimizing the use of each material's inherent strengths [4]. In pursuit of further optimizing the ecological footprint of timber-concrete composite (TCC) systems, the integration of high-performance concrete (HPC) presents a compelling avenue [5]. This paper focusses on investigating the behaviour of TCC systems, particularly the efficiency of timber-concrete shear connections. Although various types of connectors have been proposed in the past, including mechanical fasteners, notch connections, and adhesives, the emphasis will be on exploring a combination of adhesive bonding with notch shear connections. Such a joint aims to achieve high strength against shear forces while minimizing slippage, thereby maximizing the composite effect and structural performance of TCC systems [6, 7].

2. Materials used for experiment

A recipe for high-performance concrete commonly used in the laboratory environment was chosen as a reference mixture. It was developed by the Faculty of Civil Engineering, Czech Technical University in Prague utilizing predominantly local raw ma-

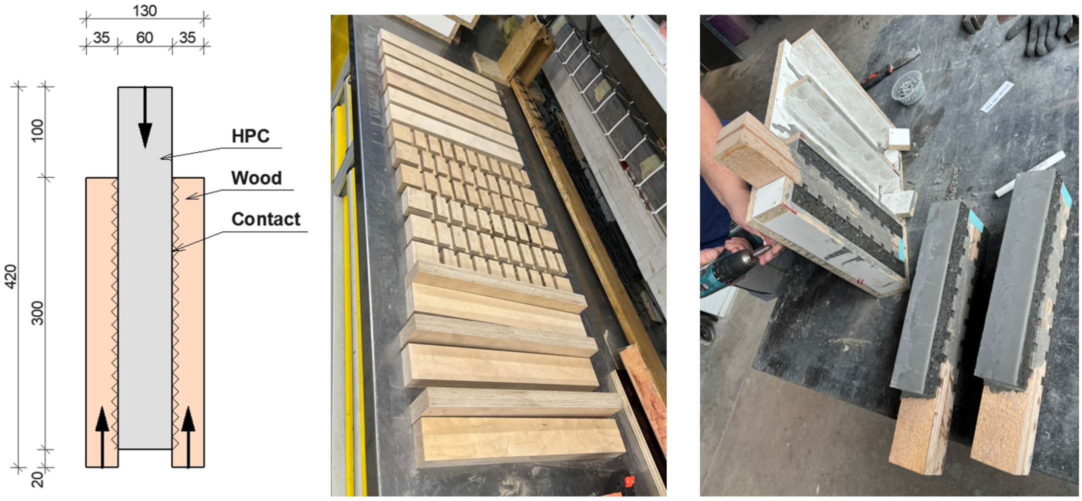

Figure 1. Specimen dimension, a view of preparing the timber base with selected notches and epoxy resin, a view of the samples after the concreting.

terials. HPC mixture design, characterized by its self-compacting fine-grained nature [7], is detailed presented in Table 1. The mixture is prepared by initially combining two types of technical quartz sand, silica flour and, with silica fume. The maximum grain size was 1.2 mm. It was without any types of dispersed fibres. The water cement ratio was 0.25 and the water binder ratio was 0.20 for this mixture. The compressive strength tested on cubes with an edge length of 100 mm was equal to 135 MPa according to the standard ČSN EN 12390-3. The flexural strength tested on prisms 40 × 40 × 160 mm was equal to 11.5 MPa according to standard CSN EN 12390-5. The same HPC recipe has been also used for several applications and research activities at the CTU like waffle and solid experimental facade elements [8–10].

Mix content	**kg m^{-3}**
Cement I 42.5R	680
Technical silica sand	960
Silica flour (ground quartz)	325
Silica fume (microsilica)	175
Superplasticizers	29
Water	171
Total	2 230

Table 1. Recipe of high-performance concrete mixture.

In the presented study, two types of commonly used wood were utilized: glulam and softwood (spruce). The required dimensions of the cross-sectional area for the testing were selected 60 × 60 mm, even considering the possibilities of HPC. As the commonly available glulam slabs had a thickness of 30 mm, so two glulam slabs were easily connected using adhesive from epoxy resin to meet the selected dimensions. Previous experience confirmed that the bond between the slabs was sufficiently strong to withstand testing without any issues [11, 12]. The solid softwood spruce pieces were used directly in the appropriate dimensions [7]. Basic table values of the mechanical parameters of the wood used are presented in the Table 2.

Timber	**Glulam (GL22C)**	**Softwood (C22)**
Compressive Strength [N mm^2]	20	20
Bending Strength [N mm^2]	22	22
Shear Strength [N mm^2]	3.5	3.8
Density [kg m^{-3}]	390	410

Table 2. Basic mechanical parameters of glulam ang softwood.

The adhesive used in this research to create a bridge in the interface between concrete and wood materials was selected epoxy resin Sikafloor 150/280 based on the previous successful experience with this epoxy resin in similar research projects [7, 8, 13]. The basic material parameters of the epoxy resin are the flexural strength of 15 MPa and the modulus of elasticity of 2.0 GPa. The specific gravity of the resin is 1 100 kg m^{-3} according to the technical data sheet of the Sika company.

3. Specimen design and preparation

In contrast to the previously mentioned "dry" and "wet" methods [14], this research adopts a third new approach, where concreting is carried out as a last step of specimen preparation. This technology aims at simple use in practice, for example, for the realization of composite elements like load bearing timber concrete sandwich panels. In the presented article two basic types of wood were utilized, glulam and softwood (spruce). The dimensions of the composites were derived from previous similar research created at the department involved push-off tests [11] and the scheme is presented in Figure 1. The concrete layers are designed outside and the wooden part inside. The

Variant description	**Code**	**Adhesive**	**Ribs**
Glulam, no adhesive, no ribs	GLU 00	–	–
Glulam, adhesive 1x, no ribs	GLU 10	1x	–
Glulam, adhesive 2x, no ribs	GLU 20	2x	–
Glulam, adhesive 1x, small ribs 12 mm	GLU 11	1x	Small 12 mm
Glulam, adhesive 1x, large ribs 24 mm	GLU 12	1x	Large 24 mm
Softwood, adhesive 1x, no ribs	SOF 10	1x	–
Softwood, adhesive 1x, small ribs 12 mm	SOF 11	1x	Small 12 mm

TABLE 3. All tested variants of glulam and softwood.

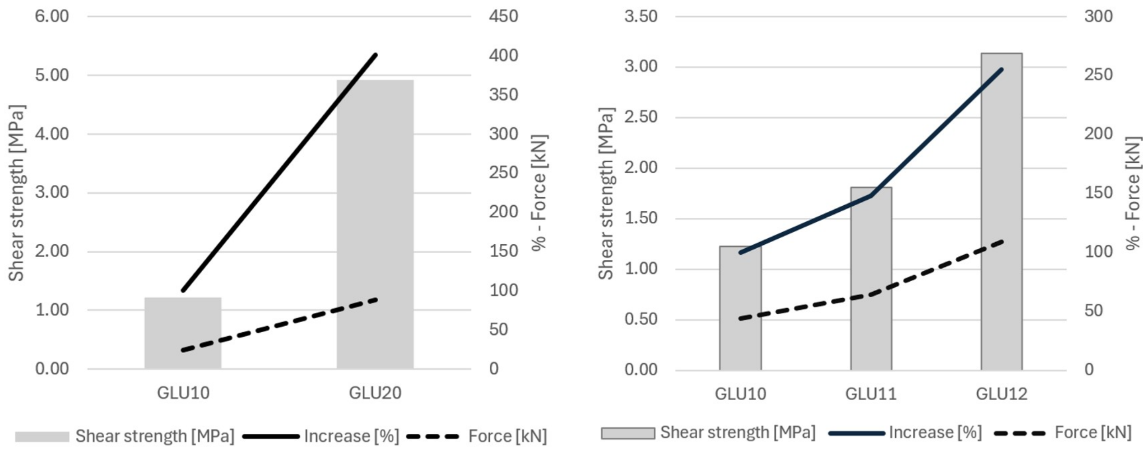

FIGURE 2. Comparison of results presented in the form of a graph, influence of method of resin application (left) and influence of prepared ribs on the shear strength (right).

designed cross-section for testing was 60 × 60 mm. As the available glulam had a thickness of 30 mm, two glulam layers were first bonded together using epoxy resin to meet the required dimensions. Previous experience confirmed that the bond between the slabs was sufficiently strong to withstand the tests without any issues [11]. The solid softwood pieces were used directly in the appropriate dimensions [7].

In Table 3 are presented all tested variants including also different notches to see their influence in effort to achieve maximum mechanical performance. A total of three specimens were always created for each mentioned variant. The first step was the cutting of wood to the required dimensions and creation of selected variants of notches. Notches were made of two kinds, always in the transverse direction to create small ribs with width 12 mm and large ribs with width 24 mm.

Next, an epoxy resin layer was applied to the wood surface, technical quartz sand with a maximum grain size of 1.2 mm was scattered to create a textured surface conducive to concrete bonding and finally fresh concrete was pour after epoxy resin hardening. To prepare these composite specimens, mould was needed to pour the concrete after the wood specimens were modified using the adhesive layer [7]. A view of the specimens in the mold after the concreting is also presented in Figure 1.

4. EXPERIMENT AND RESULTS

The focus of this article is to evaluate the shear strength in a timber-concrete composite with different modifications. The shear strength can be easily calculated by performing a push-off test. During a push-off test, force is applied through the material in the middle and derives shear stress on the interface between the wood and the concrete part. This force gradually increases until failure occurs. The maximum achieved force value is monitored and with known dimensions is later calculated as the shear stress. The loading process was performed using constant speed of loading 1.0 mm min^{-1}. The experiment was created on a hydraulic press Galbadiny Quasar 100 with a maximum load capacity of cylinder 100 kN. Due to the exceeding of maximum force, after first specimens testing was continued on a hydraulic press Controls MCC8 and cylinder with maximum load capacity of 600 kN.

Weak mechanical performance was expected from the GLU 00 group without adhesive, which was also confirmed. Some samples already experienced delamination during maturation. The measured force was minimal and random. Creating a bridge using epoxy resin gave significantly better results, but results were not stable. For some specimens GLU 10 it was visible that the bond was not well realized depending on the amount of used resin. Therefore, the GLU 20 group was created, where the first layer closed the structure of the wood after the hardening and the

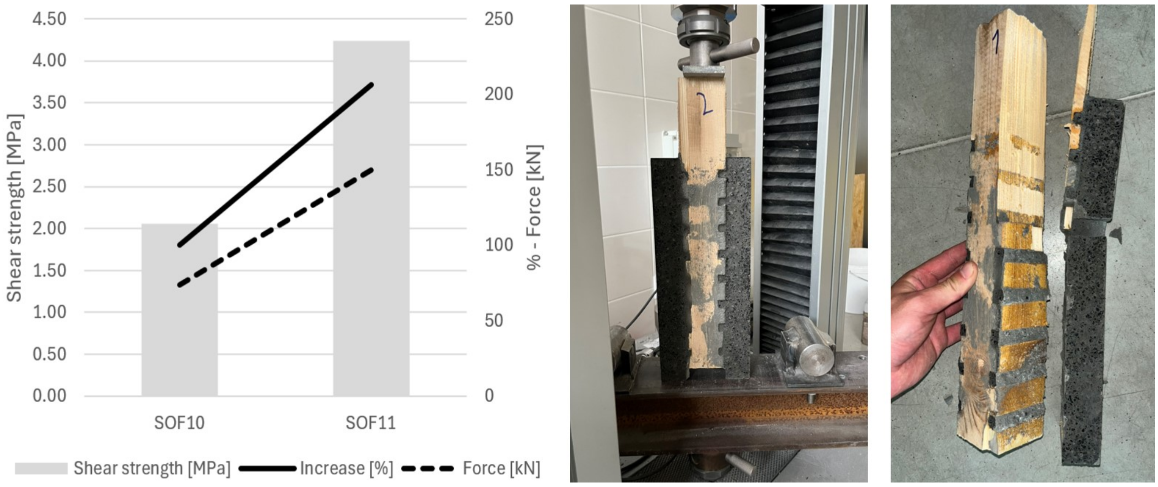

FIGURE 3. Comparison of results for the softwood – influence of ribs on the shear strength (left) and view of the sample SOF 11 before (middle) and after the loading test (right).

second layer served as an adhesive bridge fixing sand. Failure occurred only in the wood and the results of shear strength were the best achieved. The maximum shear strength was calculated at 4.92 MPa as visible in Figure 2 left. This underscores the importance of the technological process of applying glue.

The epoxy resin in general is poorly resistant to the effects of higher temperatures, so the effect of the ribs was also tested. Specimen GLU 11 featured small ribs and adhesive. With the additional ribs enhancing its shear strength and reducing the spread of results. The failure consistently occurred in the concrete at the height of the ribs. It achieved a maximum shear strength of 1.81 MPa. The alternative variant GLU 12 was more effective and demonstrated a significant improvement. It becomes evident that ribs with width 24 mm and depth 10 mm mitigate failure occurred at the height of the ribs (in concrete part). Here, the failure was simultaneously in the concrete and in the timber. The testing yielded a maximum shear strength of 3.13 MPa as presented in Figure 2 right.

Softwood has similar mechanical parameters in comparison with glulam, therefore, the number of samples was more limited. Only adhesive was used as a shear connector for SOF 10, resulting again in very varied results compared to the one with ribs. The maximum force observed was 74 kN with the correct failure in the simultaneously in the wood and concrete, while other specimens reached only 20 kN with collapse in contact area. This results in an average shear strength of 2.06 MPa. The small ribs with the softwood SOF 11 produced very strongest results, reaching a shear strength of 4.24 MPa. The failure occurred mostly in the concrete at the height of the ribs. The results in the form of graph and picture of failure specimens with the softwood are presented in Figure 3 [7].

5. CONCLUSIONS

The experimental results reveal critical insights into the bonding performance of various wood-concrete composite specimens. The initial glulam specimen, without adhesive or ribs, showed no bonding. When only adhesive was used, the results varied, highlighting the importance of precise application. The second method of adhesive application showed a significant increase in shear strength by 301 %, demonstrating the highest performance among all specimens. Moreover, this method showed reduced variance across test results, suggesting enhanced consistency in the experimental outcomes. Enhanced bonding performance was observed with the addition of ribs, where the small cross-section at the height of the ribs was the main weak point. The findings demonstrate softwood's superior performance over glulam, suggesting a stronger adhesive interaction. When considering small ribs, softwood showed a remarkable 134 % improvement over glulam. The results, which are in line with the literature, indicate that timber composite systems incorporating high-performance concrete can achieve high shear strength and overall structural performance with the use of combination adhesive and ribs. These shear connectors are crucial in maximizing the bonding efficiency and structural integrity of these composites [7].

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