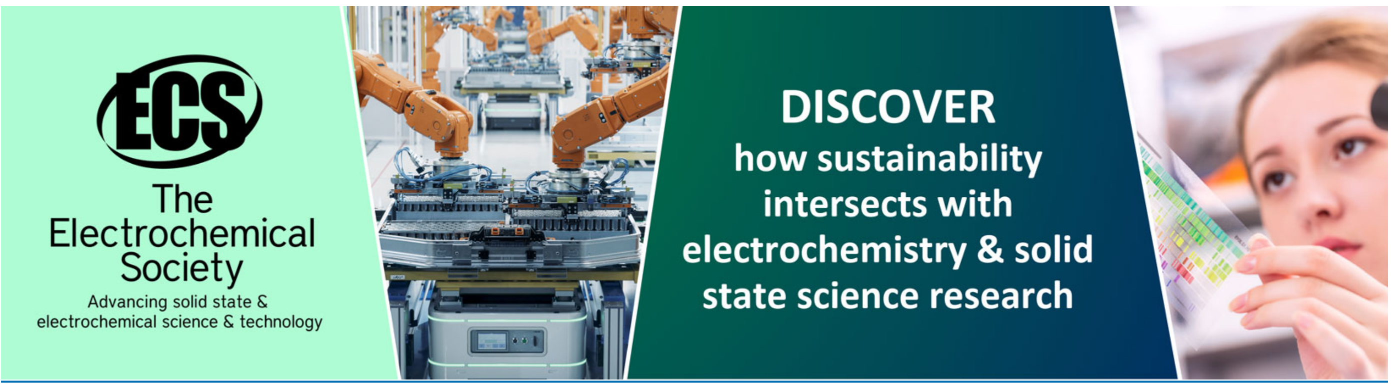
Journal of Physics: Conference Series

Experimental analysis of timber-concrete composite behaviour with synthetic fibres



Experimental analysis of timber-concrete composite behaviour with synthetic fibres

K Buka-Vaivade, D Serdjuks, D Zvirina and L Pakrastins

Institute of Structural Engineering, Riga Technical University, LV-1048, Riga, Latvia

Corresponding author's e-mail: karina.buka-vaivade@rtu.lv

Abstract. With the growing importance of the principles of sustainable construction, the use of load-bearing timber-concrete composite structures is becoming increasingly popular. Timber-concrete composite offers wider possibilities for the use of timber in construction, especially for large-span structures. The most significant benefit from combining these materials can be obtained by providing a rigid connection between the timber and concrete layers, which can be obtained by the adhesive timber-to-concrete connection produced by the proposed stone chips method. A sustainable solution involves the abandonment of steel longitudinal reinforcement. The use of such a solution in practice is often associated with fears of a fragile collapse. Therefore, the issue of how to increase the safety factor of the proposed material is topical now. The experimental investigation is made to determine the effect of synthetic fibre use on timber-concrete composite behaviour by testing a series of timber-concrete composite specimens with and without fibres in the concrete layer. The obtained results show that adding 0.5 % of synthetic macro fibres allows to abandon the use of longitudinal steel reinforcement and prevents the formation of large cracks in concrete and the disintegration of the concrete layer in case of collapse.

1. Introduction

The world population is growing rapidly. According to the U.S. Census Bureau, within a hundred years (1950 - 2050), the number of people will increase 3.8 times and amount to more than 9.7 billion. So, the principle of sustainable development – meeting the needs of the present without compromising the ability of future generations to meet their own needs – is becoming ever more important. As stocks of non-renewable resources decrease yearly, economic and rational resource use is essential. This approach also applies to the construction industry. Using composite materials in construction is one of the possibilities to ensure more efficient use of resources [1].

Composite structures are made from at least two materials with different properties, aiming to improve the final material's mechanical properties. The mechanical properties of the composite material are enhanced by combining the better properties of each, thus compensating for the material's shortcomings. In composite materials, the combined materials remain separated at the microscopic level, but the bonds between the materials are formed at the macroscopic level.

Timber-concrete composite (TCC) combines concrete – the most used man-made building material, and timber – a renewable natural resource. Both materials have their advantages and disadvantages. Combining them and ensuring their composite action makes it possible to reduce the disadvantages of these materials and obtain a structure with such benefits as a lower self-weight and better sound insulation than concrete structures, and greater stiffness and load-bearing capacity than timber structures [1-7].

The serviceability limit state (SLS) for TCC structures subjected to flexure is usually decisive. By forming a rigid adhesive connection between the layers of the composite material, it is possible to obtain a higher cross-sectional stiffness and, therefore, smaller deflections compared to structures with a semi-rigid connection between timber and concrete.

The rational use of concrete is its subjection to compression. The use of steel bars in the concrete layer increases its thickness, threatening a part of the concrete layer falling into the tensile zone. The use of steel reinforcement in the TCC structures leads to additional costs, which have become especially high in the conditions of the regional shortage of steel caused by the Covid-19 pandemic results, as well as the hostilities in Ukraine and the implemented sanctions against steel exporters. Also, the use of steel reinforcement results in higher CO_2 emissions. By using dispersed synthetic reinforcement, it is possible to avoid the use of classical steel reinforcement.

Most studies on timber-concrete composites have been carried out on a composite consisting of a plain concrete layer and solid/glulam timber beams or slabs interconnected by various types of shear connectors. The upcoming standard on the design of timber-concrete composite structures [8] provides for the reinforcement of the concrete layer with continuous reinforcement. The need for reinforcement is usually justified by possible buckling of the concrete and providing the necessary strength around the shear connectors. The use of longitudinal reinforcement means that the minimum concrete layer in a timber-concrete composite structure is 80 mm to ensure the minimum required concrete protective layer for reinforcement [9]. On the other hand, the minimum height of the timber-concrete composite slab, in that case, is 240 mm, at which the effective operation of the concrete layer is possible without subjecting the concrete to tensile stresses. Often, these material thicknesses are not determined by the structure's load-bearing capacity requirement. Therefore, classically reinforced concrete creates unnecessary additional self-weight and increases material consumption and load on supporting structures.

The use of fibre-reinforced concrete can be an effective alternative solution to the timber-concrete composite, which reduces the thickness of the concrete layer and, therefore, the self-weight of the slab. The influence of fibres on the properties of concrete depends on many factors: the shape of the fibres, the ratio between the length of the fibre and its equivalent diameter (aspect ratio) lf / df, the amount of added fibres, the orientation and distribution of the fibres, the parameters of the concrete to be used, etc. [10 – 12]. Predicting the properties of fibre-reinforced concrete is difficult. It is difficult to predict the fibres' orientation and distribution throughout the structure's volume. Studies show that the improvement in the peak strength of concrete from using fibres is usually negligible, so it is not considered in the calculations [13].

On the other hand, the effect of using fibres can be observed in different aspects. Fibres distribute local stresses, prevent the propagation of cracks in concrete, reduce the brittleness and shrinkage of concrete, significantly improving the post-peak behaviour of concrete in compression, tension, and bending, and increase the energy absorption of the structure [14 – 17]. When the first crack appears in the concrete, the fibres begin to work, forming connections or so-called bridges, which affect the concrete's deformation properties [18, 19]. It is helpful to use these effects in timber-concrete composite structures, where the concrete layer works in compression. So, the investigation aims to analyse timber-concrete composite behaviour and collapse scene with and without synthetic fibres to check the possibility of TCC safety increase. Preparation of the TCC specimens with and without synthetic fibres, static loading of specimens till collapse and determination of the effect of the fibres on the TCC behaviour were made to achieve the purpose.

2. Materials and Methods

To verify whether adding fibres positively affected TCC elements' collapse, laboratory testing of timber-concrete composite specimens was performed. Eight specimens with two different cross-sections were prepared for the static loading (Fig.1). There were two specimens with fibres and two without fibres for each specimen group. For the first group of specimens, cross-laminated timber (CLT) panels were used as the wood base. For the second group – lightweight plywood ribbed panels. Industrially produced CLT panels with a height of 60 mm (3 layers) from C24 class timber were used to produce the first group specimens. Plywood ribbed panels with C24 strength class timber beams 33x50 mm and 9 mm thick top and bottom plywood layers were also produced industrially. A 30 mm thick C20 class fine-grained concrete layer was made for both groups of specimens, using ready concrete mix Sakret BAM.

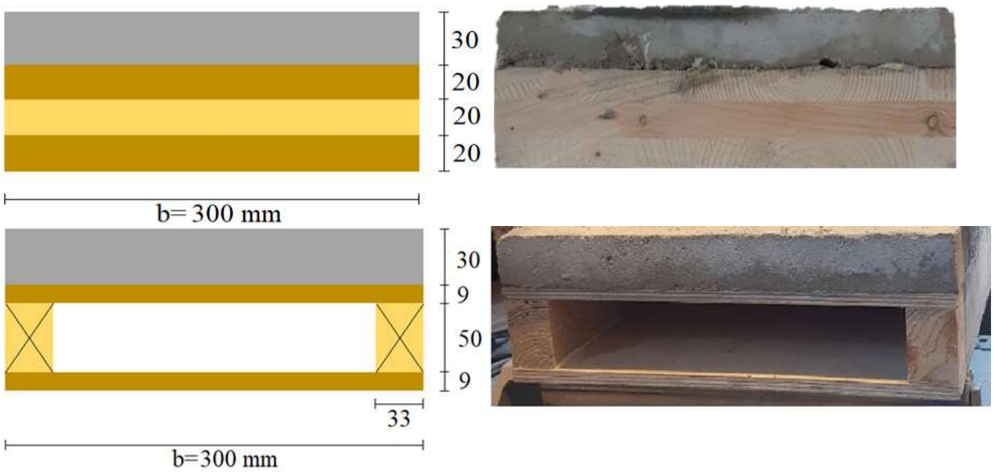


Figure 1. Two groups of the TCC specimens with different cross-sections – with CLT panel and with lightweight plywood ribbed panel.

All TCC specimens were made by the proposed stone chips method. The traditionally known two production technologies of adhesive timber-to-concrete connection – dry and wet – have significant drawbacks. These are associated with a high risk of defects in the glued connection [20, 21]. A visual specimen inspection during production, which would allow for predicting the quality of the finished product, is not possible for both methods. Since connection quality plays an essential role in the overall structure behaviour, offering the most optimal connection production technology is vital to promote the use of rigid glued timber-concrete connections in practice.

Using granite chips to ensure the glued connection between concrete and timber layers is proposed. The proposed production technology of the rigid connection between timber and concrete layers is called the stone chips method. The stone chips method involves glueing granite chips to the timber layer with 1-2 mm thick epoxy glue layer, and after the glue has dried, a fresh fine-grained concrete layer is placed [22]. Thus, the risks of creating significant defects in the rigid timber-concrete connection are significantly reduced since the influence of individual stone chips, which may form a low-quality glued connection with the timber layer, on the total area of the connection is small. The area of a possible single defect is a small percentage of the total connection surface area and is equal to the face area of a single chip. The granite chips with 16 – 25 mm (Fig.2) were glued by two-component epoxy glue SikaDur 330.

Figure 2. The production of the TCC specimens by the proposed stone chips method involves glueing granite chips to the CLT surface.

The range of 40 to 100 is generally referred to as the recommended fibre length-to-diameter ratio [23]. On the other hand, adding synthetic polymer fibres from 0.4 % to 0.8 % can strengthen the concrete matrix and achieve more effective crack control [24]. Therefore, for timber-concrete composite specimens with synthetic dispersed reinforcement, polypropylene macro fibres PP Strux 90/40 (Fig.3) are added to the concrete composition in the amount of 0.5 % of the concrete volume (Fig.4). For 40 mm long fibres with an aspect ratio of 90, the tensile strength is 620 MPa, the modulus of elasticity - 9.5 GPa and the elongation - 10%.

Figure 3. The appearance of the synthetic macro fibres PP Strux 90/40.

Figure 4. Fine-grained concrete mixture added 0.5% of synthetic macro fibres PP Strux 90/40.

The simply supported timber-concrete composite specimens with a span of 1.2 m and width 0.3 m have been tested in three-point bending until the collapse. The hydraulic loading equipment CONTROLS (Cat. C55G2) was used (Fig.5). Experimental load-displacement values are automatically fixed by connecting digital sensors to a computer.

Figure 5. TCC specimen in three-point bending.

3. Results and discussions

The values of destructive loads for timber-concrete composite specimens with and without fibres were obtained by loading the specimens in three-point bending until collapse. As shown in Fig. 6, fibres do not significantly impact the bearing capacity of the specimens. The difference in the average destructive load for specimens with CLT panels with and without added dispersed reinforcement is lower than 5 %. Still, the dispersion of the obtained load values is significant. The effect from the variability of timber properties in timber-concrete composite elements with CLT panels is greater than the effect from fibres, so unequivocal conclusions can be drawn. As the proportion of timber in the TCC element decreases, a smaller dispersion of the results and a greater increase in bearing capacity can be observed. For ribbed plywood panel–concrete composite (PWCC) specimens with fibres, the value of the average destructive load is about 13 % higher than for specimens without fibres.

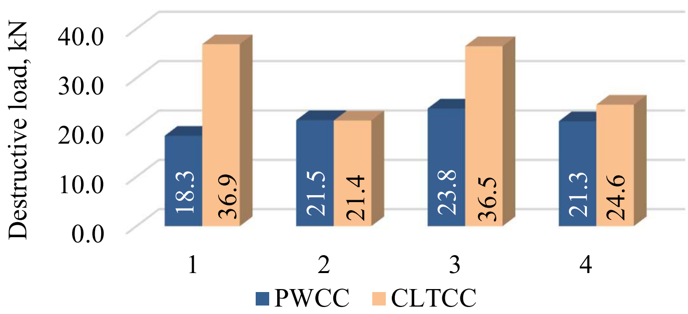


Figure 6. Values of destructive loads for TCC specimens with and without fibres, where 1 and 2 – specimens without fibres; 3 and 4 – specimens with fibres, PWCC – TCC specimens with ribbed plywood panel; CLTCC – TCC specimens with CLT panel.

The load-displacement curves for TCC specimens obtained during testing are summarised in Figure 7. Generally, a trend of increasing energy absorption from adding fibres to the concrete composition can be observed. But the dispersion of the results is still large, and the influence of timber local faults has a greater effect, which is evidenced by the behaviour of the specimen PWCC_3_with_fibres. Therefore, unambiguous conclusions about the influence of fibres on the constructive properties of the timber-concrete composite cannot be made.

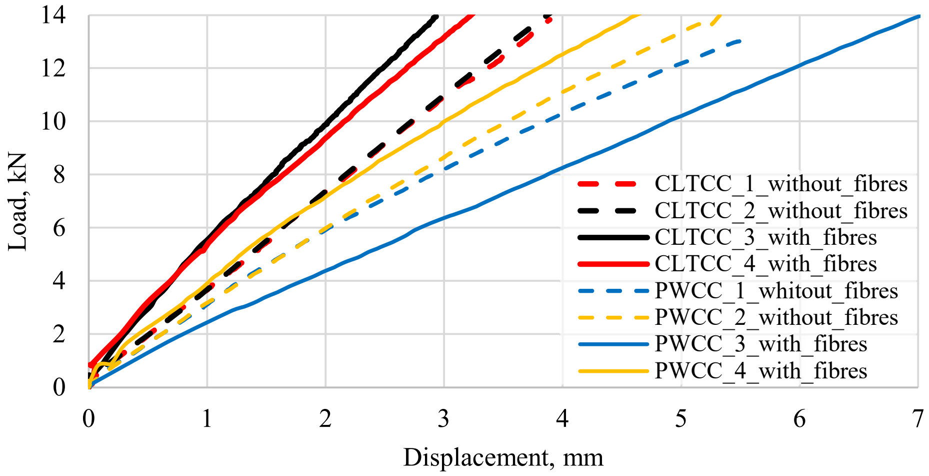


Figure 7. Load-displacements curves for TCC specimens with and without fibres, where 1, 2, 3 and 4 according to Fig.6; PWCC – TCC specimens with ribbed plywood panel; CLTCC – TCC specimens with CLT panel.

At the same time, the effect of using fibres in the collapse scenes of TCC specimens was obvious. For the TCC specimens without fibres, with plain concrete layer, a dangerous, brittle type of collapse of the concrete layer by separating concrete pieces from the timber slab was observed (Fig.8). At the same time, specimens with fibres were characterised by less brittle collapse. They did not significantly change their appearance (Fig.9). The concrete layer cracks, but the slab generally does not lose its integrity.

Figure 8. Full failure scene, nature, and development of cracks for TCC specimens with a plain concrete layer.

Figure 9. Full failure scene, nature, and development of cracks for TCC specimens with a fibre-reinforced concrete layer.

If fibres are added to the concrete composition, then several smaller cracks are formed instead of the linear development of one large crack. TCC specimens with dispersed reinforcement are characterised by microcracks smaller than the thickness of human hair. When a crack appears, the concrete continues to work because the fibres can continue to transfer stresses and distribute local stress concentration.

4. Conclusions

The positive effect on the safety of the timber-concrete composite structure from adding polypropylene fibres with an aspect ratio of 90 in the amount of 0.5 % to the concrete composition was experimentally proven.

During the laboratorian testing, were determined:

- a reduction in the brittleness of the concrete layer without traditional steel reinforcement;
- local stress distribution, which in the case of crack development, resulted in small cracks with a small opening;
- preservation of the integrity of the concrete layer with the timber layer in case of timber-concrete composite structures complete collapse.

Thus, by using dispersed synthetic reinforcement in the concrete layer, it is possible to avoid the use of classical reinforcement while maintaining the overall safety and integrity of the structure.

Acknowledgements

This work has been supported by Riga Technical University's Doctoral Grant programme DOK.BIF/21.

References

[1] Rodrigues J, Dias A and Providência P 2013 Timber-concrete composite bridges: State-of-the-art review *BioResources* 6630-6649

[2] Holschemacher K and Kieslich H 2010 Retrofitting of timber beam ceilings with the timber-concrete composite construction *Advanced Materials Research* 1095-1100

[3] Falk B 2009 Wood as a sustainable building material *Forest Product Journal* **59** 6-12

[4] Conroy K, Riggio M and Knowles C 2019 Perceptions of the environmental and health impacts of wood product use in buildings: a survey among architects on the United States west coast *BioProducts Business* 109-124

[5] Bajzecerová V 2017 Bending stiffness of CLT-concrete composite members - comparison of simplified calculation methods *Procedia Engineering* 15-20

[6] Natterer J 2004 A way to sustainable architecture by new technologies for engineered timber structures *Proceedings of the 8th World Conference on Timber Engineering* 9-27

[7] Croce P *et al* 2018 Fatigue behaviour of composite timber-concrete beams *Procedia Structural Integrity* **11** 363-370

[8] Dias A *et al* 2019 *Eurocode 5: Design of timber structures — Structural design of timber-concrete composite structures — Common rules and rules for buildings* (Brussels: CEN/TC)

[9] Holschemacher K and Kieslich H 2017 Recent developments in timber-concrete composite *CLEM+CIMAD 2017*

[10] Jansson A *et al* 2012 Experimental investigation of surface crack initiation, propagation and tension stiffening in self-compacting steel-fibre-reinforced concrete *Materials and Structures/Materiaux et Constructions* **8** 1127-1143

[11] Yusof M *et al* 2011 Mechanical properties of hybrid steel fibre reinforced concrete with different aspect ratio *Australian Journal of Basic and Applied Sciences* **7** 159-166

[12] Olivito R and Zuccarello F 2010 An experimental study on the tensile strength of steel fiber reinforced concrete *Composites: Part B* **41** 246-255

[13] Singh H 2017 *Steel fiber reinforced concrete behavior, modelling and design* (Ludhiania: Springer)

[14] Kazemi M, Golsorkhtabar H, Beygi M and Gholamitabar M 2017 Fracture properties of steel fiber reinforced high strength concrete using work of fracture and size effect methods *Construction and Building Materials* **142** 482-489

[15] Vougioukas E and Papadatou M 2017 A model for the prediction of the tensile strength of fiber-reinforced concrete members, before and after cracking *Fibers* **3** 27

[16] Simões T *et al* 2017 Influence of concrete strength and steel fibre geometry on the fibre/matrix interface *Composites Part B: Engineering* **122** 156-164

[17] Buka-Vaivade K *et al* 2019 Numerical comparison of HPFRC and HPC ribbed slabs *IOP Conference Series: Materials Science and Engineering* **660** 012054

[18] Abdul-Razzak A and Mohammed Ali A 2011 Modelling and numerical simulation of high strength fibre reinforced concrete corbels *Applied Mathematical Modelling* **35** 2901-2915

[19] Bhargava P, Sharma U and Kaushik S 2006 Compressive stress-strain behavior of small scale steel fibre reinforced high strength concrete cylinders *Journal of Advanced Concrete Technology* **1** 109-121

[20] Buka-Vaivade K and Serdjuks D 2022 Behaviour of timber-concrete composite with defects in adhesive connection *Procedia Structural Integrity ICSI 2021 The 4th International Conference on Structural Integrity*, *Funchal, Madeira, Portugal, 30 August – 2 September 2021* 563-569

[21] Buka-Vaivade K *et al* 2021 Rigid connection with granite chips in the timber-concrete composite *Environment Technology Resources Proceedings of the International Scientific and Practical Conference* **3** 36-39

[22] Buka-Vaivade K, Serdjuks D and Pakrastins L 2022 Cost factor analysis for timber–concrete composite with a lightweight plywood rib floor panel *Buildings* **12** 761

[23] Akio M, Masaki O, Mitsuro M and Junichi Y 1987 *Synthetic fiber suited for use in reinforcing cement mortar or concrete and cement composition containing same* (European Patent Office Patent EP0286112A2)

[24] Chaudhary M, Srivastava V and Agarwal V 2014 Effect of waste low density polyethylene on mechanical properties of concrete *Journal of Academia and Industrial Research* **3** 123-126