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WHITE PAPER

DELTABEAM® WITH HYBRID TIMBER FLOORS

LOAD TRANSFER TESTS

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INTRODUCTION

Hybrid structures are a recent trend in the construction industry. The concept of hybrid structures is to combine two or more different types of materials so that the strong points of each of them are maximized. In fact, there are often many key drivers for the choice of material, such as structural strength, speed of construction on site and aesthetics as well. Combining materials allows to obtain the optimal solution that blends all stakeholders' requirements on a project, from structural point of view to fast and safe construction process, to environmental criteria and sustainability.

In this regard, the use of DELTABEAM® Composite Beam [2], [3] with mass timber floors allows us to combine renewable and ecological material, timber, with two of the strongest materials, steel and concrete. On the one hand, DELTABEAM® Composite Beam allows for a slim floor solution with longer spans than traditional full timber structures, where the structural grid might be limited by deflection or vibration requirements. This results in saving building height significantly. On the other hand, mass timber floors are manufactured to enhance the performance of wood, which gives high strength ratings, but significantly reduces weight compared to other floor types (Figure 1). Such combination results in an efficient hybrid structure that offers several benefits.

BENEFITS OF DELTABEAM® WITH TIMBER FLOORS

DELTABEAM® can be used with both solid timber and composite timber slabs for almost any kind of building. Different depths of DELTABEAM® are available to match the slab height as well as the thickness of the steel plates is designed case by case, depending on load conditions. The main benefit is that the beams don't project from the soffit as they are integrated in the slab, which reduces the total floor thickness between 10 to 30 percent (Figure 2).

FIGURE 1. MASS TIMBER FLOOR PRODUCTS (ADAPTED FROM [6])

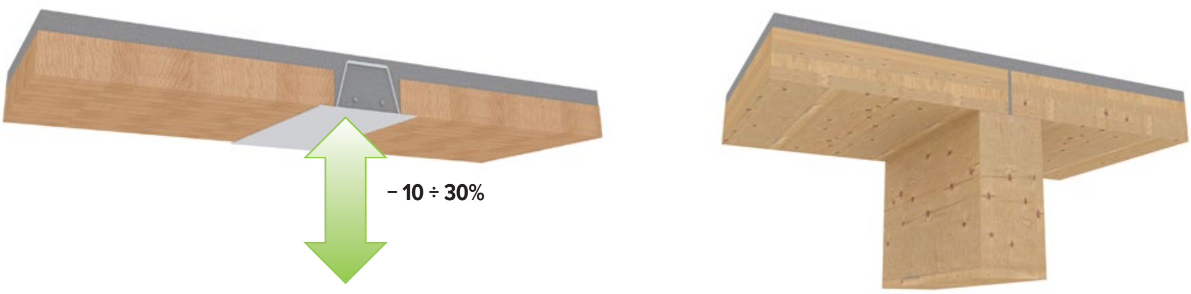

FIGURE 2. COMPARISON BETWEEN DELTABEAM® AND TYPICAL TIMBER STRUCTURE

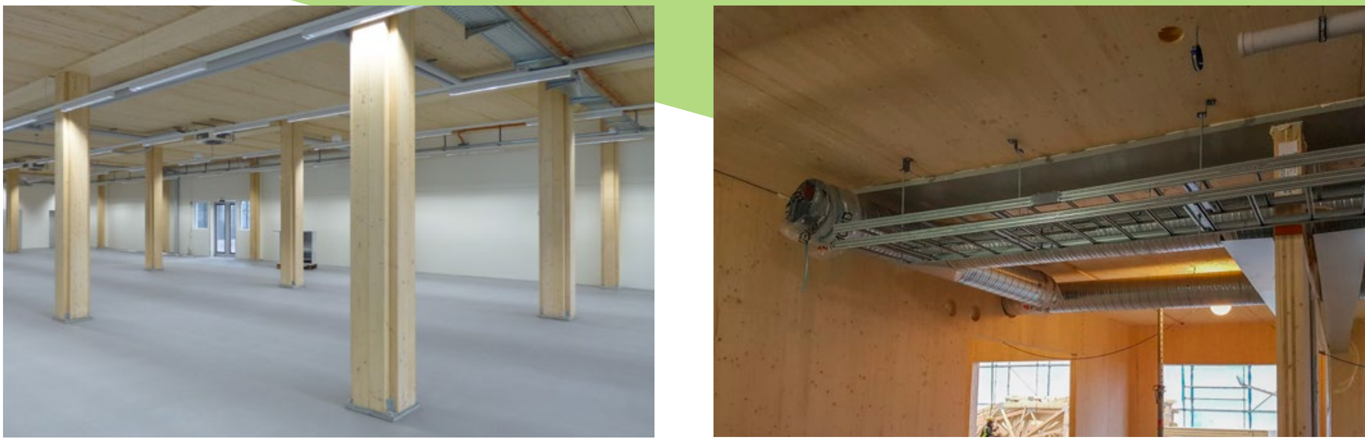

FIGURE 3. DELTABEAM® SLIM FLOOR SOLUTION AND TECHNICAL INSTALLATIONS

FIGURE 4. D- AND DR-TYPE DELTABEAM® WITH TIMBER FLOOR

DELTABEAM® composite action between concrete and steel allows longer spans that create open spaces with minimum columns. Structural grids up to 9x9 m^2 can be constructed to give architectural freedom and layout flexibility. From aesthetic point of view, the bottom plate of DELTABEAM® can be even covered with timber boards so as to enhance the interior design by having a complete timber ceiling.

Smooth ceilings enable additional room space and easier technical installations, which is useful as HVAC systems increasingly require space in modern buildings (Figure 3). In particular, complicated penetrations of service lines through the structure can be avoided, making both building and maintenance more efficient and quicker. At the same time, heating and associated energy requirements can be reduced. In fact, a slim floor solution minimizes the heat exchange with the exterior environment by reducing the aspect ratio of building façades and therefore having a more compact building design. In addition, timber floors provide good insulating properties too.

As far as the construction process, the typical delta-shape of the steel beam profile allows for easy installation of timber slabs units on the ledge at both or one side, for middle or edge beam respectively (Figure 4). Speed of installation is optimized with prefabricated timber structural elements, which can be constructed in factories and then assembled on site quickly and then even uninstalled and reused in the prospective of circular economy.

Moreover, fireproofing is already integrated into DELTABEAM® since fire rebars and webs act as tensile reinforcement in the event of a fire. Resistance of main structural load bearing element is then guaranteed based on project fire rating requirement and the need for a complex fire painting on-site is eliminated.

Finally, the choice of DELTABEAM® Green matches perfectly with the sustainability of timber floors, as it is made with 90% recycled steel. The environmental impact of DELTABEAM® Green has been reduced significantly compared to traditional steel structures, as stated by Environmental Product Declaration [5], and the use of timber further reduces the carbon footprint, especially when local material is used.

RESEARCH PROGRAM

Peikko initiated a research program on DELTABEAM® Composite Beam with timber floor solutions to provide information to customers for a safe design. In fact, the behavior of concrete, steel and timber as a whole needs evidence as the solution is innovative and currently not comprehensively covered by the standards. Ongoing investigations include fulfillment of vibration requirements and behavior in fire conditions.

The first phase of such investigations focused on the load transfer capacity of DELTABEAM® floor joint, i.e., how the load is transferred from the floor to the beam. In the final condition, the loads are transferred to DELTABEAM® through a compression arch against the inclined web (Figure 5). Compression forces are taken by the concrete surrounding DELTABEAM® steel profile while joint rebars carry tension forces.

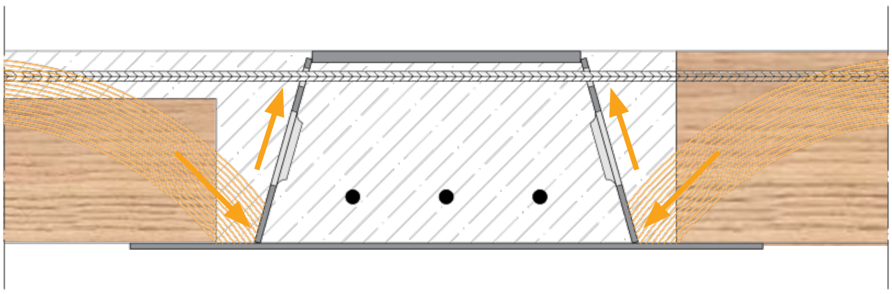

FIGURE 5. LOAD TRANSFER MECHANISM IN FINAL SITUATION

	Specimen	Timber edge	Ledge
DELTABEAM® Timber slab	A1	Vertical	yes
	A2	Inclined	yes
	A3	Inclined	**no**
	A4	Inclined with pockets	**no**
DELTABEAM® Composite Timber slab	B1	Vertical	yes
	B2	Inclined	yes
	B3	Inclined	**no**
	B4	Inclined with chamfers	yes
	C1	Vertical	yes
	C2	Inclined	yes

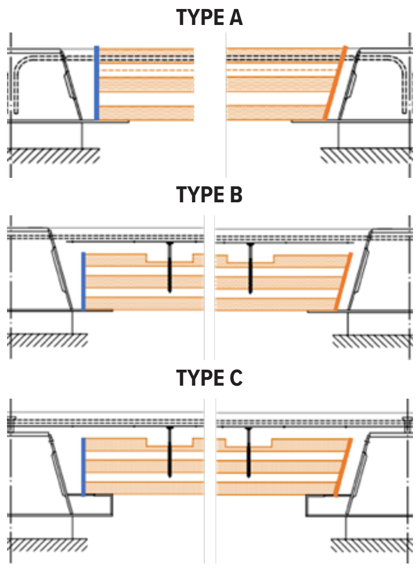

FIGURE 6. OVERVIEW OF THE SPECIMENS

Full-scale load transfer tests on both timber and composite timber slabs supported by DELTABEAM® Composite Beam were carried out. Cross-laminated timber (CLT) was selected as being one of the main representatives of mass timber products. The slab unit consists in a multi-layered panel made of lumber, in which each layer of boards is placed crosswise to adjacent layers, thus resulting in a biaxial load bearing element. The CLT floor units were produced by Stora Enso [1], which supported this part of the research program.

Ten specimens were tested, as shown in Figure 6. Detailing of the interface between the timber panels and the outer concrete of DELTABEAM® was selected to cover possible cases that are used in projects and to test new configurations as well, which could improve the resistance of the joint by tailored geometry cut along the side of the timber panel.

Three specimens had vertical edge of the timber panel, while the others had the timber edge cut to have the same inclination as DELTABEAM® web. The supporting ledge was removed in three of the specimens with the inclined timber edge in order to simulate the fire condition. In fact, the steel ledge loses a major part of stiffness and resistance when exposed to fire. The artificial removal of the ledge then emulates, or even maximizes, this condition. As a consequence, the support of the slab, or of the remaining part of the slab after charring, relies only on the inclined web and on joint reinforcement (Figure 7).

TEST SETUP

The test setup is shown in Figure 8. DELTABEAM® was 1.5 m long and the slabs spanned 3 m on each side. CLT timber panels had different thicknesses for plain timber (200 mm, Type A specimens) or composite timber slab (180 mm, Type B and C specimens), each of them with a 5-layer assembly. The depth of DELTABEAM® standard profile was selected accordingly.

Composite timber slabs had a concrete topping thickness equal to 1/3 of the total thickness, as it occurs in most of real cases. Both topping flush with DELTABEAM® top plate (Type B) and continuous topping over the beam (Type C) were tested. In the latter case, DELTABEAM® had a downstand.

As the aim of the tests was limited to investigate the load capacity of DELTABEAM® floor joint, the central part of the beam was fully supported from the bottom along its length so that only the ledge was unsupported and free to deform under the load. The thickness of the ledge was 6 mm, which is the minimum default. The other side of the slab was laying on a roller support.

The slabs were loaded with a line load applied at a distance from the center line of DELTABEAM® that equals three times the thickness of the slab, so to maximize the shear in the area close to the beam. Compared to distributed load in normal design conditions, this is an unfavorable condition, which forces the shear failure to occur close to the beam. The failure was then expected to occur in the slab, either in timber or in concrete, before reaching the failure of the support.

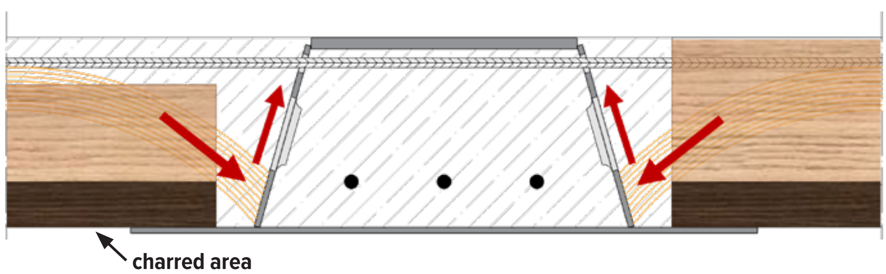

FIGURE 7. LOAD TRANSFER MECHANISM IN FIRE SITUATION

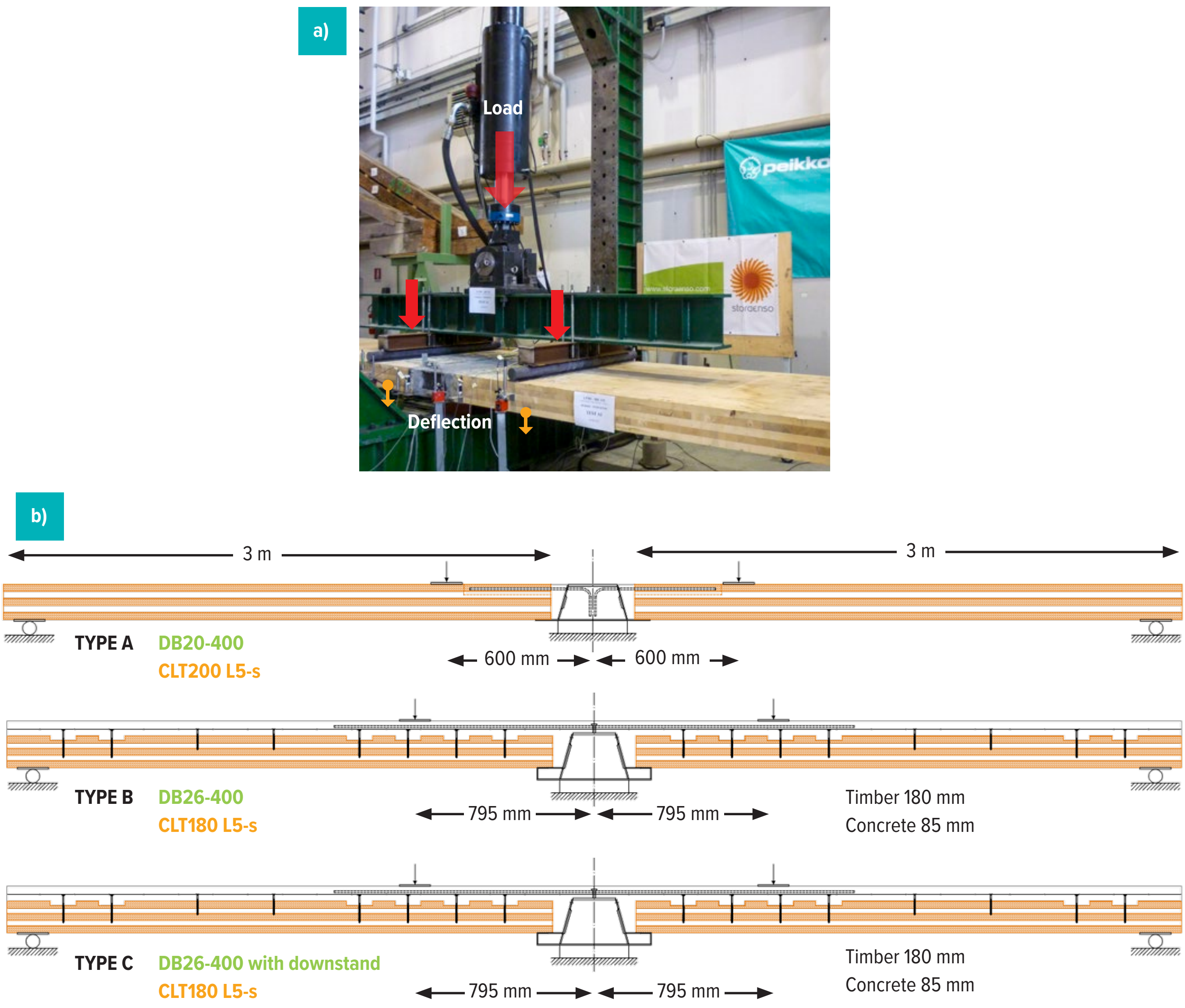

FIGURE 8. A) LAB TEST SETUP; B) SPECIMENS' DIMENSIONS

FIGURE 9. JOINT REINFORCEMENT FOR TIMBER AND COMPOSITE TIMBER SLABS

INTERACTION BETWEEN DELTABEAM® AND THE SLABS

Transverse reinforcement was provided in order to tie the slab units to DELTABEAM® and to secure the load transfer. In fact, the role of joint rebars is to take the horizontal tension forces that develop at the support under vertical shear load. Joint rebars are usually placed into DELTABEAM® web holes or air holes. In case of timber slab, grooves were cut into the panels for placing the rebars, while for composite slabs the rebars were placed inside concrete topping (Figure 9). Such reinforcement was designed for the expected failure load and provided with the sufficient anchoring length.

In addition, a connection between the panel and the topping is needed in timber-concrete slabs to get the composite action [7]. In this case, a notched connection was selected (Figure 10). Such connection transfers interlayer forces by bearing adjacent materials in the notch. Large head screws are used as connectors against the uplifting force. The screws were designed based on the withdrawal capacity of the thread considering the concrete shear failure mode [4].

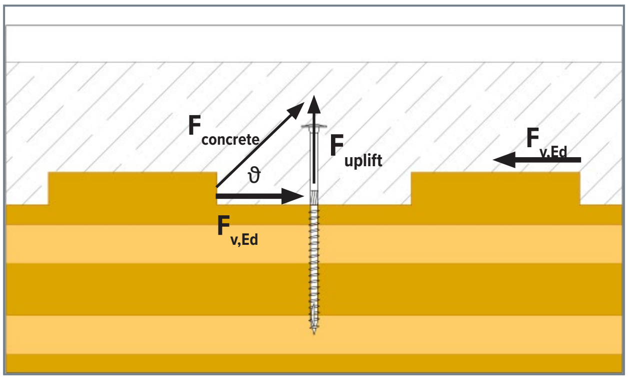

FIGURE 10. NOTCHED CONNECTION FOR COMPOSITE TIMBER SLABS (ADAPTED FROM [4], $F_{v,Ed}$ ACTING SHEAR FORCE)

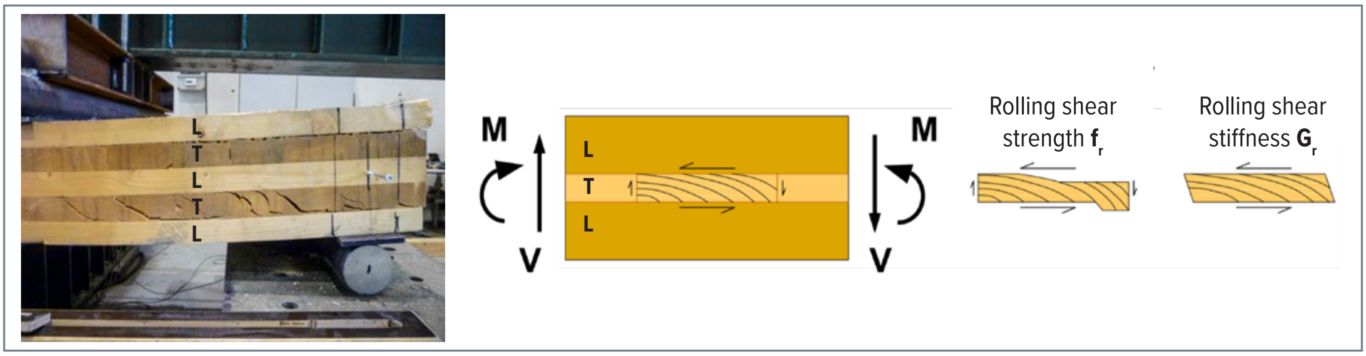

FIGURE 11. TYPICAL ROLLING SHEAR FAILURE IN CLT PANEL

FIGURE 12. ROLLING SHEAR FAILURE AND LEDGE DEFLECTION IN SPECIMEN A2

RESULTS

CLT SLABS

CLT panels are generally prone to fail in rolling shear, as timber exhibits limited resistance to shear forces that act orthogonal to grain direction. In fact, rolling shear failure occurs in the transverse layers where the timber fibers start to roll one over the others under shear stresses, which develops the typical crack pattern shown in Figure 11.

As being the weakest link of the chain, the low rolling shear capacity may govern the performance of CLT panels under circumstances such as concentrated loads and short spans. This was actually the case of the considered test setup, where high shear stresses were induced in the panel area close to DELTABEAM® and the ledge deflected up to 20 mm (Figure 12). Nevertheless, the peak load always exceeded the estimated failure load. In fact, the peak load was from two to three times greater than the design load level corresponding to a 6x6 m^2 grid with 3 kN/m^2 live load (Figure 13).

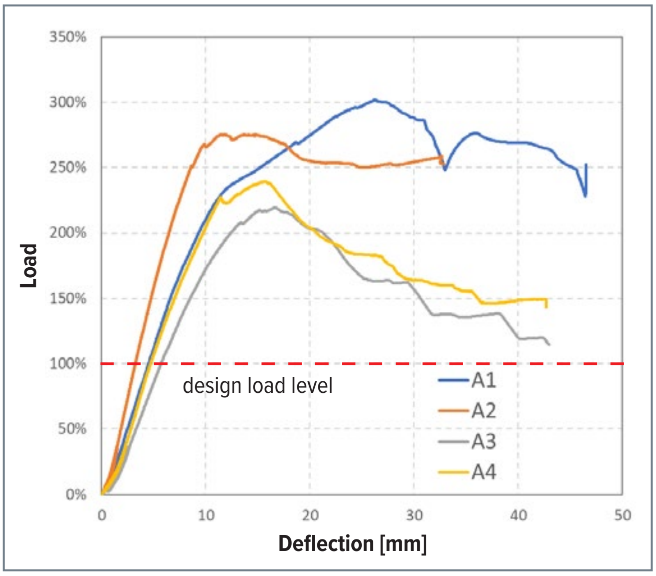

FIGURE 13. LOAD DEFLECTION CURVES OF TIMBER SLAB SPECIMENS

FIGURE 14. TIMBER PANEL FAILURE IN SPECIMEN A3 (WITHOUT DELTABEAM® LEDGE)

The load-deflection curves also show the reduced stiffness of the joint in the specimens where DELTABEAM® ledge was removed to simulate the fire condition. However, the load carrying capacity was maintained even for a slab deflection up to 40 mm, thus proving the effectiveness of the load transfer mechanism. Moreover, the comparison between the curve referring to the specimens A3 and A4 shows that the improved geometry of timber-concrete interface has a beneficial effect on the load capacity of the joint. In fact, the concrete inside the pockets that are cut along the timber edge offers additional support to the slab, especially when the ledge is no more bearing (Figure 14).

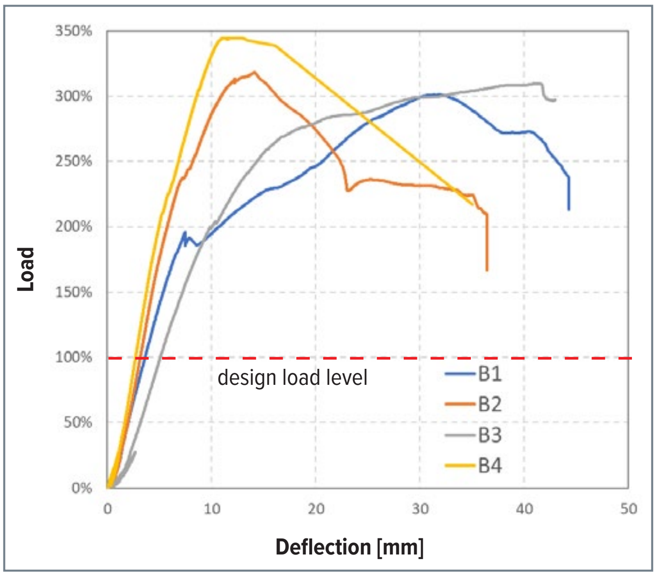

FIGURE 15. LOAD DEFLECTION CURVES OF COMPOSITE TIMBER SLAB SPECIMENS

COMPOSITE CLT SLABS

Timber-concrete composite systems generally provide several benefits from both structural and environmental point of view. As vibration and acoustic requirements might be determining in the design, timber-concrete composite slabs can offer better performance compared to timber slabs of equal thickness. This is due to the combined effect of the materials, as concrete provides more mass and hence decreased acceleration, while timber keeps the structural solution light. Because of this and considering the greater thickness of the slab (265 mm), test results of all the composite specimens showed higher strength and greater stiffness than the timber ones (Figure 15). In this case, the peak load was approximately three times greater than the design load level corresponding to a 7x7 m^2 grid with 3 kN/m^2 live load.

In particular, specimen B4 reached the maximum capacity of the actuator (100 tons) without failing. The failure occurred then by keeping the load constant for few minutes. This shows the beneficial effect of the chamfers that are cut along the edge of the end face of the timber panel. In fact, the geometry of the joint improves the load transfer capacity by guiding the development of concrete struts close to DELTABEAM® web holes.

FIGURE 16. CONCRETE TOPPING CRACK PATTERN DEVELOPMENT IN SPECIMEN B2

FIGURE 17. FAILURE MODES IN COMPOSITE TIMBER SPECIMENS: BENDING, ROLLING SHEAR AND SCREW PULL-OUT

The failure of the composite timber slabs was mainly due to cracking of the topping which started from the separation between timber and concrete in the area close to the beam that had no connectors to take the tension forces. The crack pattern clearly showed the direction of tensile stresses, which were orthogonal to the orientation of compression forces pointing from the applied load to the notches (Figure 16). Rolling shear in timber and/or bending failure of the slab occurred as well, which usually follows in CLT panels due to the loss of composite action between the layers. Slight pull-out failure of the large head screws was also observed, as the actual failure load exceeded the expected one (Figure 17).

FIGURE 18. FAILURE OF COMPOSITE TIMBER SLAB SPECIMENS WITH BEAM DOWNSTAND

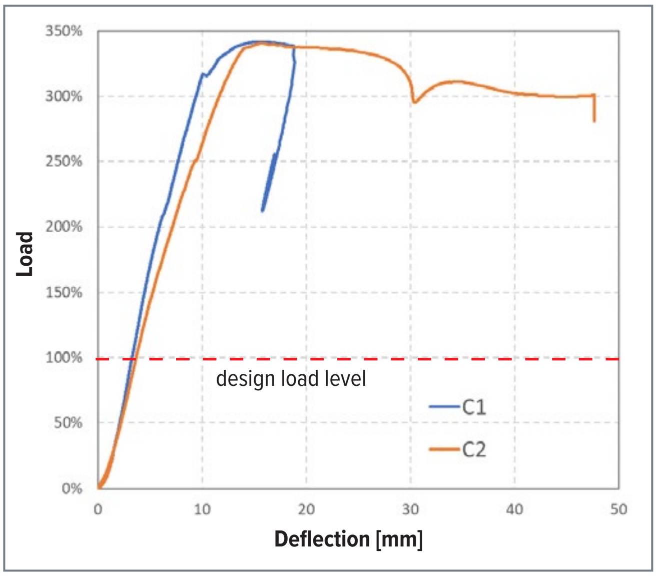

FIGURE 19. LOAD DEFLECTION CURVES OF COMPOSITE TIMBER SLAB SPECIMENS WITH BEAM DOWNSTAND

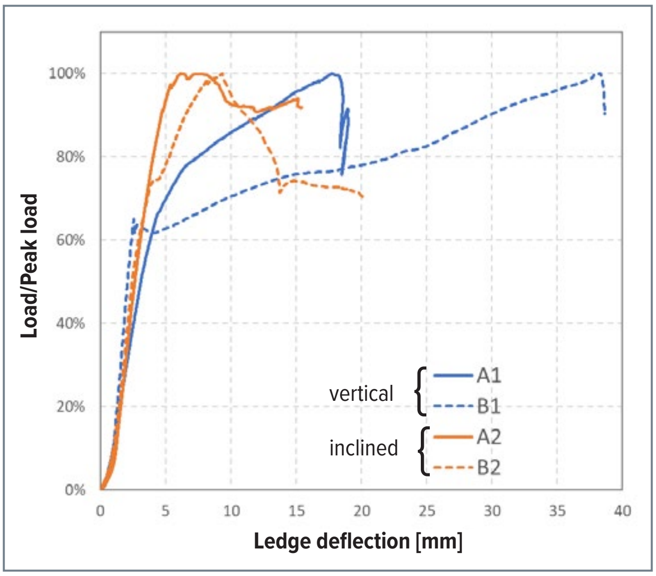

FIGURE 20. COMPARISON OF LEDGE DEFLECTIONS WITH VERTICAL AND INCLINED TIMBER EDGE

COMPOSITE CLT SLABS WITH BEAM DOWNSTAND

The behavior of composite slabs with DELTABEAM® and the downstand was similar to the above mentioned one, in the sense that the failure occurred by a combination of concrete topping cracking and rolling shear in the timber panel (Figure 18). However, the specimens showed a much higher stiffness, which is due to the rigid bearing provided by the downstand to the slab. As a result, the global behavior is not much affected by the joint detail, i.e., vertical or inclined timber edge, as shown by similar load-deflection curves (Figure 19).

DESIGN RECOMMENDATIONS

Based on test results, some design recommendations can be drawn. Both the vertical and inclined edge of the timber panel give adequate resistance to the joint. However, the inclined one could be preferred, as during the tests it showed higher failure loads and limited ledge deflections (Figure 20). It should be anyhow noted that the high line load close to the end of the CLT panel caused significant rotation at the support for both edge configurations, which resulted in greater ledge deflection than in normal design condition. Friction reaction forces that develop between the outer concrete of DELTABEAM® and the inclined side of the panel are beneficial to the load transfer mechanism. When the inclined timber edge is used, notches can be cut locally to the timber panel edge along the joint at web hole position to ease concrete pouring and guarantee proper filling.

The results confirmed that joints of the composite slabs are stiffer and more resistant when compared to timber ones with same thickness. This solution is optimal with DELTABEAM®, being a composite structure itself. Reinforced concrete topping provides continuity between adjacent slabs, and transverse rebars can be easily installed through DELTABEAM® steel profile. Moreover, the use of composite slabs with DELTABEAM® allows to achieve slim floors with wide spans in both beam and slab direction, which is generally not possible with traditional timber structures.

Specimens A4 and B4 proved that a tailored geometry of the timber edge can have a beneficial effect in the load transfer capacity of the joint. Such details were tested together with inclined edge. However, same details could be used when the timber edge is vertical, in order to balance production and installation benefits of vertical edge and better performance of the interface geometry. In any case, the use of joint rebars is essential to tie the slab to the beam and to ensure the load transfer. During the test, the strains that were measured by strain gauges applied on the rebars at concrete timber interface cross-section exceeded the yielding, due to the high level of load, which was far beyond the design load condition. Nevertheless, any rebar failure such as pull-out or blow-out failure occurred even in timber slabs without concrete topping, which showed perfect embedment of the reinforcement into concrete-filled in grooves and proved the effectiveness of the tying system.

CONCLUSIONS

The use of DELTABEAM® Composite Beam with mass timber floors is promising for building hybrid structures that conveniently combine the need for efficient structural design, fast construction and sustainability. Existing projects have already shown the versatility of the system (Figure 21) and on going investigation will provide more evidence on safety and reliability of the DELTABEAM® solution.

ACKNOWLEDGEMENTS

Peikko greatly acknowledges Stora Enso for the support in the research program and the Laboratory of the University of Trento (Italy) for performing the tests.

FIGURE 21. PROJECTS WITH DELTABEAM® AND TIMBER FLOORS (FIND OUT MORE AT WWW.PEIKKO.COM/REFERENCE)

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