PEIKKO
WHITE PAPER

HIGH FIRE PERFORMANCE OF DELTABEAM® SLIM FLOOR JOINTS WITH TIMBER SLABS

Published: 01/2023

Salla-Mari West
M.Sc.
R&D Engineer
Peikko Group Corporation

Simo Peltonen
M.Sc.
Senior R&D Manager
Peikko Group Corporation

1. INTRODUCTION

The use of mass timber products like cross-laminated timber (CLT) slabs has grown in floor structures because of its strength, dimensional stability, and rigidity [8]. Fireproofing a massive timber product is often unnecessary since such products often have sufficient load-bearing capacity even without fire protection [9]. Therefore, CLT slabs can be left exposed. The char zone insulates the remaining cross-section which retains its structural capacity. [8]

DELTABEAM® is a slim-floor composite beam that is integrated into the floor, which enables smooth ceilings and does not require additional fireproofing. The evaluation of the fire resistance of DELTABEAM® is based on Eurocodes, standard fire tests and design guidelines obtained from tests. High fire resistance without fire protection is achieved by infill concrete and fire rebars, that are installed inside DELTABEAM® profile at the factory, when needed. The fire rebars and the DELTABEAM® webs act as tensile reinforcement in the event of a fire. [1]

Peikko has been investigating the performance of the joint area between DELTABEAM® Composite Beam and timber floors, to fill the gaps in standards with facts. Peikko started by investigating the load transfer capacity of the joint area between DELTABEAM® and timber floor in ambient temperature, i.e., how the load is transferred from the floor to the beam [5]. The performed charring test and 90-minute fire test with loading were continuity to these load transfer tests. The fire tests proved that DELTABEAM® Composite Beam used together with CLT slabs works in fire situation without any additional fireproofing under the beam nor under the CLT slab. DELTABEAM® Composite Beam is an excellent solution for creating a slim floor structure with timber slabs which can be left exposed as seen in *Figure 1*.

Figure 1. *To increase sustainability Peikko's Slim Floor Structure solution is created with DELTABEAM® Green and CLT slabs [14].*

2. FIRE DESIGN OF CONNECTIONS

The joints are generally the weakest parts of a timber structure in fire situation [10]. Therefore, connections require careful design [11]. The fire resistance of an unprotected traditional timber joints of actual standards is usually less than 30 minutes [10]. Connections can be protected by using concealed connections protected by charring of timber or by using fire-rated gypsum boards. In some cases, also intumescent paints or seals may be used to provide protection for exposed connections. [8]

Steel has high thermal conductivity. Due to this, fasteners and plates that are directly or indirectly exposed to fire may heat up and not only lose strength but also conduct heat into the timber product. This may cause charring on the exposed surface and around the fastener. Protecting the connections prevents the steel from excessive heating and therefore losing its strength. Protecting the connection also prevents the steel causing accelerated charring around it, which could lead to loosening and failure of the connection. [11] Connections protected by the charring of the timber often lead to massive timber structures. DELTABEAM® enables to create a slim floor structure while simultaneously joining the beam and CLT slab together with encapsulated transverse reinforcement.

The 90-minute loaded fire test proved that the interface between DELTABEAM® Composite Beam and timber floor can transfer loads in the fire conditions in edge and intermediate beam. Transverse reinforcement anchored to the grooves of timber slab ties the beam and slab together and secures the load transfer in both ambient temperature and in fire situation, see *Figure 2*.

Figure 2. Transverse reinforcement secures the load transfer.

The two-hour charring test included DELTABEAM® with commonly used timber slab details used in an innovative way with Slim Floor Structure. Based on experience and performed fire design calculations, the most suitable joint details were selected for the tests.

3. DESIGNING DELTABEAM® WITH CLT SLAB

3.1. CLT SLAB DURING FIRE

When exposed to fire, the temperature of the uncharred timber part is below 100 degrees except the timber layer with 10 mm to 20 mm thickness above the charred layer [10]. At 200–300°C, chemical compounds decompose in a process known as pyrolysis. The pyrolysis will gradually spread along the timber, leaving a charring area behind.[12] Due to the fall of charred layers, the carbonization of the CLT board is not linear and progresses at several carbonization rates. The fall of charred layers occurs when the fire reaches the polyurethane adhesive joint of the CLT sheet. After this, the charred layer is supposed to fall. The next layer starts to char at a higher speed. After some time, the charring rate returns to the original value. [10]

To fire design CLT slabs it is recommended to use the reduced cross-section method described in EN 1995-1-2 [12]. The charring depth is the distance between the outer surface of the original member and the position of the char-line and should be calculated from the time of fire exposure and the relevant charring rate. The position of the char-line should be taken as the position of the 300-degree isotherm. [2]

Due to the protecting effect of the DELTABEAM® ledge, the infill concrete and Peikko's unique solution the charring depth in the joint area was not as deep as in the middle of the CLT span. After the 90-minute loaded fire test, the specimen was demolished to investigate the charring of the structure. *Figure 3* proves that the charred timber above the DELTABEAM® ledge stays in place. This charred timber keeps protecting the joint area after the bottom lamella of the CLT slab has fallen.

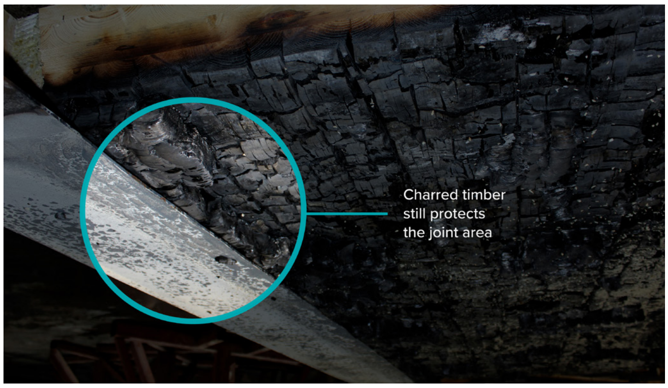

Figure 3. Specimen from below after 90-minute loaded fire test.

3.2. REDUCED CROSS-SECTION METHOD

In the reduced cross-section method, the parts of the cross-section with assumed zero strength and stiffness are removed and do not contribute anymore to the resistance of the cross-section [2]. The specimen for the charring test had seven different details which were equipped with thermocouples. DELTABEAM® Composite Beam was not fireproofed in any of the cross-sections. *Figure 4* presents the finished specimen for the charring test. The temperature data from the charring test proved that the charring depth is smaller in the joint area between DELTABEAM® Composite Beam and CLT slab than in the middle of the CLT slab area even without any additional fireproofing.

Figure 4. Specimen for the two-hour charring test without loading. CLT 200 L5s and CLT 280 L7s timber slabs were placed on the DELTABEAM® Composite Beam ledges or downstands. DELTABEAM® and the CLT 200 L5s slabs had equal depth.

There are different options for the edge geometry of the timber slab, like vertical or inclined end cut shown in *Figure 5*. The geometry of the CLT slab end doesn't affect to the load-bearing capacity of the structure. *Figure 6* shows the temperatures in joint area between DELTABEAM® and CLT slabs without any additional fireproofing under the beam nor under the CLT slabs. As seen in *Figure 6*, both vertical and inclined end cuts can be used in CLT slabs. The charring rate with the vertical cut is higher in the beginning but in the end the effective charring depth is about the same for both cuts. 100 mm from the CLT soffit the temperature has settled to 100 degrees for both cuts.

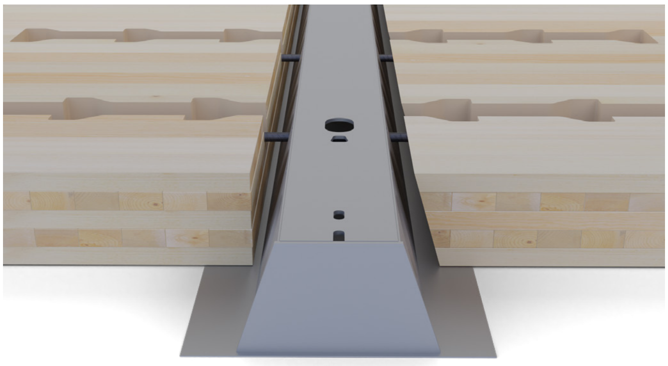

Figure 5. Vertical and inclined end cut on the CLT edge.

Before the charring test the effective charring depth was calculated for the CLT slab without any additional fire proofing. According to SFS-EN 1995-1-2 and the CLT product charring rate, the effective charring depth will be 108 mm [2,6]. After the test the effective charring depth was calculated according to SFS-EN 1995-1-2 and the temperature data. *Figure 6* shows that the 300-degree char-line at 120 min is between 60 mm and 80 mm. To be on the safe side 80 mm will be selected. According to SFS-EN 1995-1-2, material close to the char-line has zero strength and stiffness [2]. Therefore, the effective charring depth for both cuts is 87 mm. With both CLT end cuts the effective charring depth proves to be less in the joint area between DELTABEAM® and CLT slab than the calculated effective charring depth at the midspan of the CLT using CLT product charring rate.

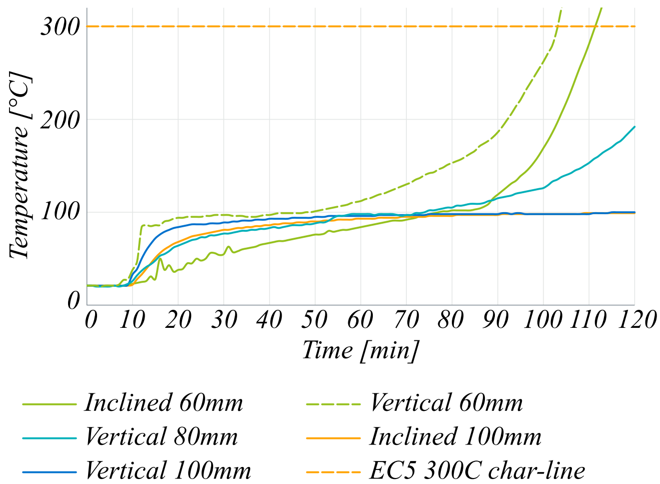

Figure 6. Temperature in the CLT slab in the joint area, 60-100 mm from the CLT soffit.

Based on the extensive measurement data from the various details it could be clearly seen that DELTABEAM® Composite Beam had no negative impact on the charring rate of the CLT panel in any of the investigated details. DELTABEAM® enables slim-floor solution and can be used together with various common timber floor details used in the real-life projects.

3.3. LOAD-BEARING CAPACITY, INTEGRITY, AND INSULATION

In the case of fire, structures shall be designed and constructed in such a way that they maintain their load-bearing function during the relevant fire exposure. Where fire compartmentation is required, the elements forming the boundaries of the fire compartment, including joints, shall be designed, and constructed in such a way that they maintain their separating function during the relevant fire exposure. The criteria for integrity and insulation must be fulfilled when relevant. [2] In the 90-minute fire test with loading all REI90 requirements for load-bearing capacity, integrity and insulation were met. In the REI90 fire test CLT 200 L5s timber slabs were placed on the DELTABEAM® Composite Beam ledges. The D20-300 and DR20-215 DELTABEAM®s and the CLT slabs had equal depth. There was no additional fire proofing used neither in DELTABEAM®s nor in CLT slabs. The load was kept constant the entire 90-minute fire test. *Figure 7* presents the finished specimen for the 90-minute fire test.

Figure 7. Specimen for the 90-minute fire test with loading. The load arrangement simulated DELTABEAM® and CLT slab structure with 8 m CLT span, 1.7 kN/m² permanent load and 5 kN/m² live load (ψ_1 = 0.7). The defined factor ψ_1 is the same as used in congregation areas, shopping areas, and F traffic areas.

Deflections were measured in the middle of the CLT elements, in the middle of the intermediate DELTABEAM® and in the middle of the DR-type DELTABEAM®s. The deflections at 90-minute were between 40 mm and 50 mm for DELTABEAM®s and CLT slabs which are less than $L^2/400d$ mm = 136 mm (depth of the specimen d is 200 mm, and the span L is 3300 mm). The deflection rate was less than $L^2/9000d$ mm/min = 6.05 mm/min. Therefore, the criteria of the load-bearing capacity R were met.

The average temperature rise for the whole structure at 90 min was 62 degrees. This is less than the 140 degrees limit value for the insulation criterion. The highest temperature rise was in thermocouple TC20, 92 degrees at 90 min. The highest temperature rise was less than 180 degrees which fulfils the insulation criteria of any point of the specimen. Based on the big number of measured temperatures in the joint area between DELTABEAM® Composite Beam and CLT slabs the insulation I criteria for average and the highest temperature rise were met.

There were no flames on the unexposed surface. There were no gaps in the specimen. Based on the visual observations the integrity E criteria were met.

3.4. LOAD TRANSFER

Figure 8 shows how the loads are transferred to DELTABEAM® through a compression arch against an inclined web also in fire situation. Due to this, charred timber part remains between the beam ledge and the uncharred timber slab providing an insulation to the joint area during fire. More information about the load transfer in erection stage and in final composite stage can be found in DELTABEAM® technical manual for timber structures.

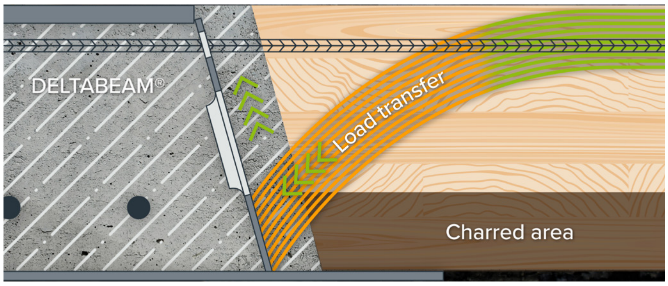

Figure 8. Load transfer in fire situation.

Based on visual observations of the REI90 fire test, the charring happens only at the bottom as expected. The joint concrete is clean without any damages. The fire has not burned through the joint. After the fire test when specimen had cooled down, the specimen was cut into three pieces at mid spans of the CLT parallel to the beam. Finally, section of CLT slab was removed next to edge and intermediate DELTABEAM® to investigate the charring in the joint area. *Figures 9* and 10 present that there is about half of the second lamella remaining in the joint area while in the middle of the CLT span the second lamella is already fully charred. The depth of the uncharred timber in the middle of the CLT span was between 120 mm and 135 mm which means that about 70 mm of the CLT slab depth was charred. In intermediate and edge beam cases about 50 mm of the CLT slab depth was charred away. The specimen continued to burn during disassembling the load arrangement and lifting the specimen. Due to this, the measured remaining timber slab depths are on the safe side. The measured charring depths during demolition support the temperature data measurements and proves that the calculated effective charring depth is conservative.

Figure 9. Charring in the DELTABEAM® and CLT slab joint, next to the joint concrete.

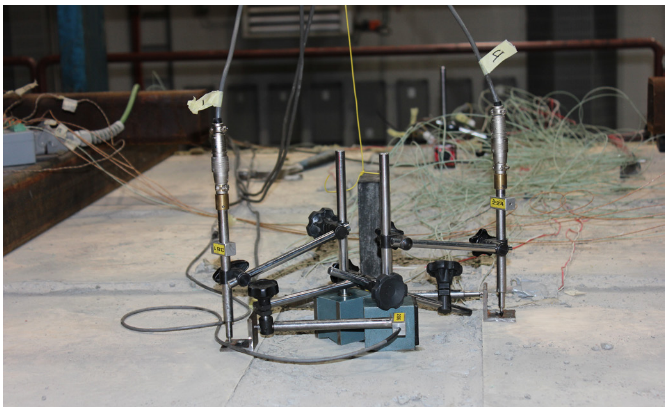

Figure 11. Displacements in the joint area were measured in the middle of the beam span in vertical and horizontal direction.

Figure 10. Charring in the middle of the CLT span.

All displacement transducers were set on DELTABEAM® as a reference. Displacement between the top end corner of CLT slab and the top plate corner of DELTABEAM® is measured in vertical and horizontal direction. The measured relative displacements show that the joint area performs well in fire situation. The assembled displacement sensors can be seen in *Figure 11*. The results prove that the transverse reinforcement ties DELTABEAM® Composite Beam and CLT slab together securing the load transfer.

3.5. DELTABEAM® FIRE DESIGN

DELTABEAM® Slim Floor Structure always includes a full design service by Peikko – structural design calculations, structural drawings of beams and connection detailing instructions – to be approved by the customer [1]. The reduction factor for the mechanical properties of structural steel and reinforcing bars is used in elevated temperatures [7]. The temperature measurements from the charring test and from REI90 fire test prove that current DELTABEAM® Composite Beam fire design is also safe with timber floors. Therefore, using CLT slabs with DELTABEAM® doesn't require any additional fire design to the current approved standard DELTABEAM® Composite Beam fire design method.

3.6. DESIGNING TRANSVERSE REINFORCEMENT

Transverse reinforcement was anchored to the grooves of CLT slab. Purpose is to tie DELTABEAM® and the CLT slab together and secure the load transfer. Rebars with 12 mm diameter and 600 mm spacing were applied for DELTABEAM®s. With intermediate beam the transverse reinforcement goes through the air holes at the top end of DELTABEAM® webs.

The rebar length depends on the required length of the grooves and the required anchorage length according to SFS-EN 1992-1-1 [4]. The required length of the grooves depends on the needed amount of the notches in order to properly transfer the loads from CLT slabs to DELTABEAM®. The minimum concrete cover is calculated according to SFS-EN 1992-1-1 [4]. For the REI90 fire test specimen the anchorage length of the rebars was determined by the length of the grooves. Reinforcement must extend beyond the last notch to the end of the groove.

The force in the rebar creates pressure to the notches as seen in *Figure 12*. The needed amount of the notches in the grooves of CLT slabs depends on the pressure force. The transverse reinforcement needs to extend beyond the last notch to the end of the groove so that the load is transferred from CLT slab to DELTABEAM®. Peikko's special design of the grooves helps to distribute the pressure in the end of the groove. It is important to have wide enough grooves, especially when the transverse rebar is not only securing the load transfer, but also carrying unsymmetric load for example. Having wide enough concrete block along with sufficient amount of reinforcement prevents the concrete from cracking.

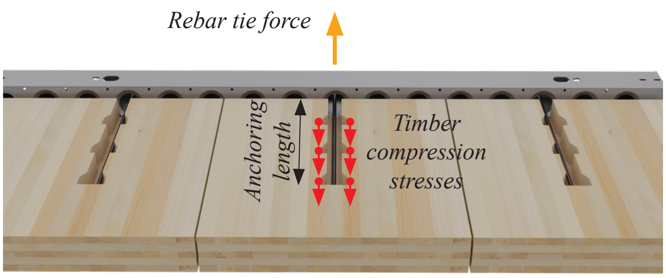

Figure 12. Force in transverse rebar creates pressure in the notches.

Figure 13 presents the normal stresses in the transverse rebars during the 90-minute loaded fire test. The normal stresses were highest in edge beam situation due to unsymmetric load. The highest normal stress was in edge beam situation in transverse rebar *1B*. *Figure 14* presents the stress-strain curve for rebar *1B*. The normal stress increases linearly and then decreases linearly following the same path. The transverse rebars do not yield since there is no permanent deformations according to the stress-strain curves.

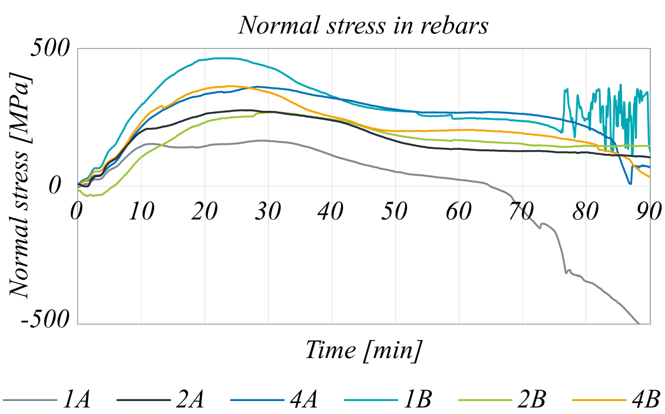

Figure 13. Normal stresses [MPa] vs time [min] in the transverse rebars. "1A", "1B", "4A" and "4B" are strain curves of the transverse rebars in the edge beam situations."2A" and "2B" are strain curves of the transverse rebars in intermediate beam.

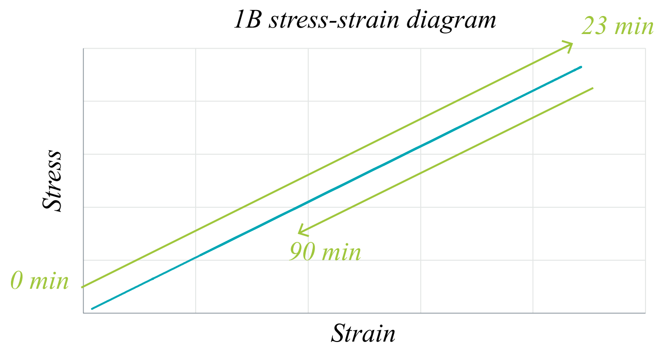

Figure 14. Normal stresses vs strain in the transverse rebar "1B". The stress-strain curve is in blue. The green arrows in the diagram reflect the change of the normal stress during the REI90 fire test.

Figure 15 presents the bending stiffness of DELTABEAM® Composite Beam during the 90-minute loaded fire test. The bending stiffness is reduced the most during the first 30 minutes. At the same time the normal stresses in the transverse rebars increase the most during the first 30 minutes.

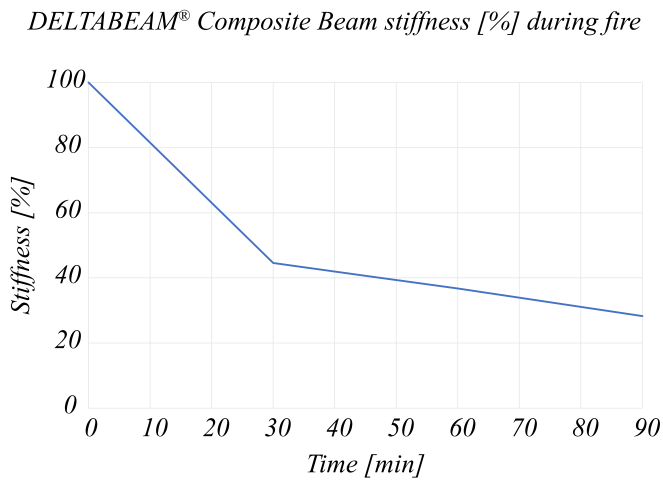

Figure 15. Bending stiffness of DELTABEAM® Composite Beam vs time [min] during the 90-minute loaded fire test.

3.7. EDGE BEAM SITUATION

The transverse reinforcement in the edge beams is designed to resist the force caused by unsymmetric load and to secure the load transfer. In case of unsymmetric load the transverse rebars should be located as low as possible considering the temperature in fire situation, which could affect the resistance of the rebars. One option is to place the transverse reinforcement through the web holes depending on the project. *Figure 16* shows the designed transverse reinforcement in edge beam situation.

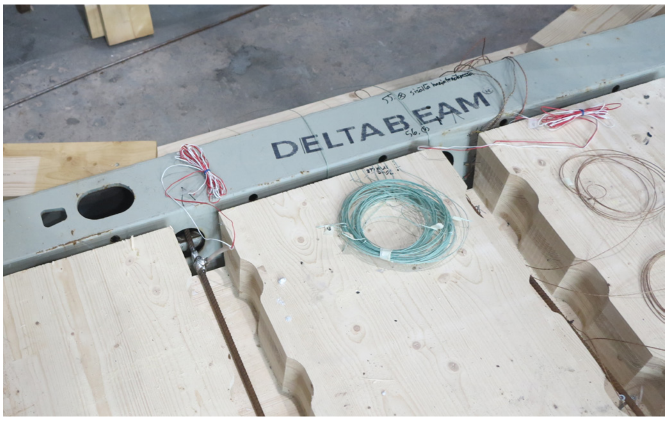

Figure 16. Reinforcement in edge beam situation.

After the timber under the groove has charred away the concrete starts to heat up following the standard fire exposure. According to the measurement data this assumption is on the safe side. Temperature in the transverse rebar was 114 degrees at 90 minutes in the joint area. The temperature on the bottom of the groove was 100 degrees at 90 min.

CLT slabs should have wider grooves in case of high load on the transverse rebar for example due to unsymmetric load. The grooves in the fire test specimen for edge beam situation were two times wider than in intermediate beam case because of unsymmetric load to prevent the concrete from cracking. *Figure 17* presents how the load eccentricity causes pressure to the topmost CLT layer. The pressure must not exceed the design compressive strength of timber along the grain.

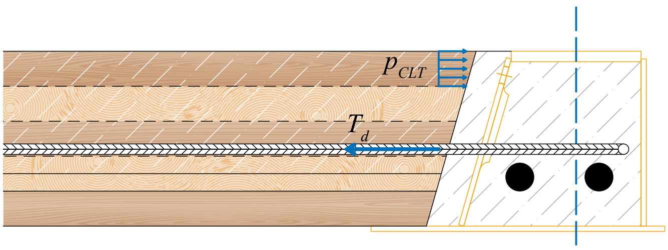

Figure 17. Reinforcement in edge beam situation.

3.8. VIBRATION

Even though this is not an issue in the event of a fire, we want to address the importance of the verification of the dynamic properties of the timber floors. For mass timber floors the performance in human-induced vibration due to walking excitation is often the determining design criterion in residential, public or office buildings. There are two common ways to provide a criterion for limiting vibration. The second alternative is to limit the lowest frequency of the floor, which is considered as a simpler and more conservative approach. These floors are casually nominated as 'low-frequency floors'. Since CLT slabs supposedly have less stiffness and mass than concrete slabs, a limit for the lowest frequency is often given as high as 8 Hz to 9 Hz depending on the code or national annex. In practice, meeting the limit of 8-9 Hz with low-frequency floors may not be sensible from an economic point of view, especially if there is also a requirement for longer spans. By neglecting the limit for the lowest frequency and concentrating on the response itself, many different beam – slab combinations can reach acceptable performance. Use of the composite structure formed by CLT and concrete topping is especially effective and has great potential to reduce the depth of the floor. Peikko can help to fulfil economically the common design criteria for human-induced vibration due to walking excitation with different DELTABEAM® - CLT floor types.[13]

4. CONCLUSIONS

According to the measurement data and observations during demolition after the fire test DELTABEAM® ledge seems to have a protecting effect concerning the charring depth development. DELTABEAM® has no negative impact on the charring rate of the CLT panel. Based on the fire test results, the load transfer between the beam and CLT slab works as assumed in the DELTABEAM® design. The DELTABEAM® temperatures in the fire tests were clearly on the safe side compared to the temperatures used in DELTABEAM® design.

Based on the deflection and deflection rate measurements the load-bearing function was maintained during the 90-minute loaded fire test which satisfied criterion for resistance R. Based on the big number of temperature measurements inside the structure, it can be stated that average and maximum temperature rises were within the limits. Therefore, the criteria for insulation I were satisfied. Based on observations during the fire test, during the disassembly and during the demolition DELTABEAM® Composite Beam met the criteria for integrity E.

ACKNOWLEDGEMENTS

The authors would like to thank Stora Enso for providing the CLT slab elements to the tests and technical support in planning the fire tests. Peikko also greatly acknowledges Eurofins Expert Services Oy (Finland) for performing the tests.

REFERENCES

[1] Peikko Group: DELTABEAM® Slim Floor Structure With Timber Construction - Technical Manual, 2022.
[2] SFS-EN1995-1-2 - Eurocode 5: Design of timber structures - Part 1-2: General - Structural fire design, Brussles: CEN European Committee for Standardization, 2004.
[3] SFS-EN 1168 G.3.5
[4] SFS-EN 1992-1-1 - Eurocode 2: Design of concrete structures. Part 1-1: General rules and rules for buildings, Brussles: CEN European Committee for Standardization, 2004.
[5] Peikko Group: DELTABEAM® WITH HYBRID TIMBER FLOORS LOAD TRANSFER TESTS, 2022.
[6] Stora Enso: Cross-laminated timber (CLT), 2022. https://www.storaenso.com/en/products/mass-timber-construction/building-products/clt
[7] SFS-EN1994-1-2 - Eurocode 4: Design of composite steel and concrete structures. Part 1-2: General rules - Structural fire design, Brussles: CEN European Committee for Standardization, 2004.
[8] Richard McLain and Scott Breneman. (2019). Fire Design of Mass Timber Members. WoodWorks. https://www.woodworks.org/wp-content/uploads/Wood_Solution_Paper-Fire-Design-of-Mass-Timber-Members-WoodWorks-Apr-2019.pdf
[9] Puuinfo: PALOTURVALLINEN PUUTALO Asuin- ja toimitilarakentaminen, 2021. https://puuinfo.fi/wp-content/uploads/2021/05/Palokirja_netti_kokonainen.pdf
[10] SUOMEN LIIMAPUUYHDISTYS RY ja PUUINFO OY: Liimapuukäsikirja osa 2, 2015. https://puuinfo.fi/wp-content/uploads/2020/07/Liimapuuk%C3%A4sikirja-Osa-2.pdf
[11] Technical Guide for the Design and Construction of Tall Wood Buildings in Canada Second Edition 2022
[12] Stora Enso: CLT Technical brochure, 2017. https://www.storaenso.com/-/media/documents/download-center/documents/product-brochures/wood-products/clt-by-stora-enso-technical-brochure-en.pdf?mode=brochure#page=24
[13] Peikko Group: PERFORMANCE OF DELTABEAM® – CLT FLOORS IN HUMAN-INDUCED VIBRATION, 2021.
[14] Peikko Group: DELTABEAM® Green to lighten a building's environmental footprint. https://media.peikko.com/file/dl/i/3Ks4MA/pU8nKtc2hwLFq1RQFKd9Cw/PeikkoWhitePaper_DELTABEAMtolightenbuildingsenvironmentalfootprint_web.pdf