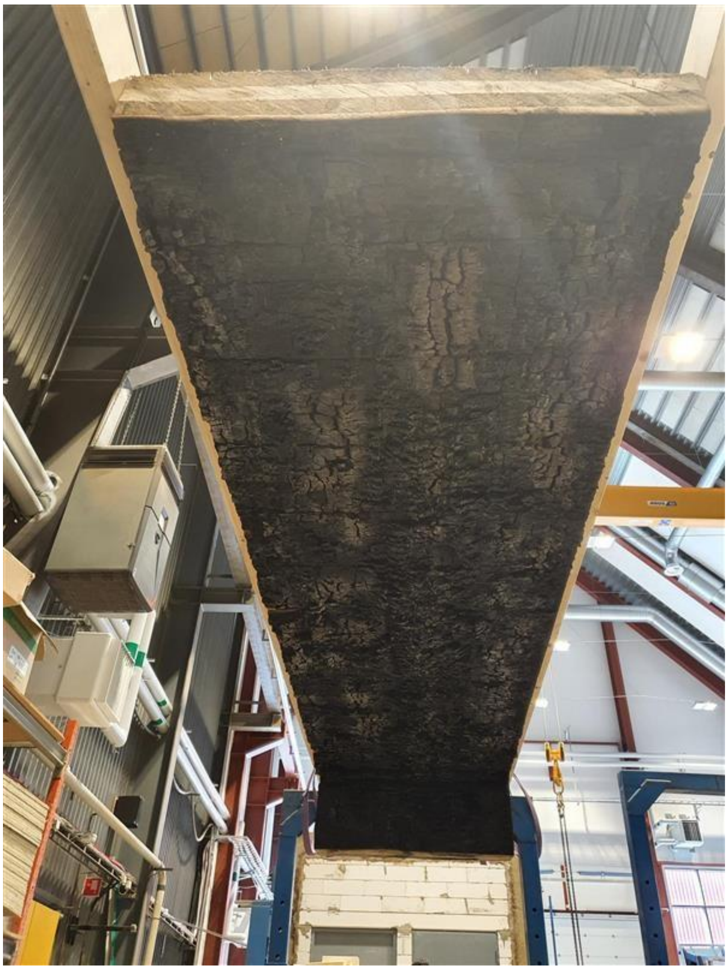
DIVISION SAFETY AND
TRANSPORT
FIRE RESEARCH



Post-Fire Rehabilitation of CLT

Daniel Brandon
Johan Sjöström
Fredrik Kahl

RISE Report 2021:67

Post-Fire Rehabilitation of CLT

Daniel Brandon
Johan Sjöström
Fredrik Kahl

Abstract

Post-Fire Rehabilitation of CLT

Engineered mass timber materials such as CLT have been increasingly implemented as a structural material for tall or larger buildings in recent years. Most studies have been conducted on the structural performance of timber exposed to fire, but the number of studies focusing on post-fire rehabilitation of mass timber have been limited. As increasingly large timber buildings are being realized, for insurance purposes it becomes increasingly important to ensure that a building can be repaired after a fire.

This report presents a case study of the repair of a section of a CLT ceiling after a significant fire. The specimen is obtained from a recent compartment fire test and is positioned and oriented in a way that is representative for on site rehabilitation. The repair was done in six steps:

1. Mapping the thickness of the charred or damaged layer
2. Design and planning
3. Removal of the char layer
4. Planing of the surface including corners
5. Gluing procedure of replacing lamella
6. Finish the surface to meet architectural requirement

A new method for determining the grade of damage, the method for planing the specimen, the adhesive type, the glue pressing methods were designed for the rehabilitation exercise. In addition, the layup of the CLT is changed to prioritise flexural stiffness and bending capacity over shear capacity, as they generally govern the structural capacity of CLT floors.

After the six-step repair was done, the specimen was cut in half to perform two similar structural bending tests. The results indicate that the flexural stiffness which is generally governing the load bearing capacity of floors, is fully restored by the rehabilitation work. The results also indicate that bending capacity, which can be governing for relatively short floor spans, is restored and possibly increased by the rehabilitation work. The shear capacity which is only critical for short floor spans in combination with very high loads is, however, reduced, as the experimental shear capacity is 18% lower than the characteristic shear capacity.

Key words: Repair, char, timber, fire, damage

RISE Research Institutes of Sweden AB

RISE Report 2021:67
ISBN: 978-91-89385-57-3
2021

A summary video of the post-fire repair exercise is shown on:

https://www.ri.se/en/what-we-do/projects/fire-safe-implementation-of-mass-timber-in-tall-buildings

Content

Preface

This report provides results of a research project on fire-safe implementation of visible wood in tall timber buildings. The main funder of the project is the **US Forest Service (USFS)** under the **US Department of Agriculture** (*USFS Grant Number 2019-DG-11083150-022).* The project owner is the **American Wood Council** (AWC), and **Research Institutes of Sweden** (RISE) is the contractor for this research project.

Other project partners and funders of this project are:

- **Katerra** providing ANSI/APA PRG 320 (2018)-compliant CLT;
- **KLH** providing ANSI/APA PRG 320 (2018)-compliant CLT;
- **Henkel** providing the required ANSI/APA PRG 320 (2018)-compliant adhesive and additional funding,
- **Boise Cascade** providing ANSI A 190.1-2017 compliant glued laminated timber; **USG** providing Type X gypsum boards;
- **Rothoblaas** providing mass timber screws, sealants, tapes, resilient profiles and equipment for lifting anchors mass timber members;
- the **Softwood Export Council** providing shipment costs of US products to the test site in Sweden;
- **Brandforsk** providing additional funding for the inclusion of façade extension measurements. The façade measurements are out of the scope of this report.
- **Dynea AS** providing a gap filling PRF adhesive for the case study presented in this report.

A Steering Group was assembled for this project, comprising of:

- Kevin Naranjo (USDA)
- Kuma Sumathipala, Jason Smart, Kenneth Bland (AWC)
- Sean DeCrane (Building & Life Safety Technologies, UL)
- Gordian Stapf, Christian Lehringer, Daniel Current, Chris Whelan (Henkel)
- Hans-Erik Blomgren (Katerra)
- Sebastian Popp, Johannes Habenbacher (KLH)
- Kyle Flondor, Ajith Rao, Young-Geun You (USG)
- Susan Jones (Atelier Jones)
- Rodney McPhee (Canadian Wood Council)
- Dan Cheney (Boise Cascade)
- Hannes Blaas, Andres Reyes, Paola Brugnara (Rothoblaas)

All steering group members provided in-kind technical contributions in this project.

Besides the members of the reference group, Ronny Bredesen at Dynea, Harald Krenn at KLH, have provided valuable technical advice for the post-fire repair case study discussed in this report. Rune Ziethén at RISE has performing the bending tests and provided technical advice.

1 Introduction

Engineered mass timber materials such as CLT have been increasingly implemented as a structural material for tall or larger buildings in recent years. Current architectural trends include the implementation of visible mass timber. During a fire, the exposed mass timber can become involved in the fire and start charring. Although many studies have been conducted to study the structural performance of fire exposed timber, and recent studies have focussed on the contribution of timber to the fire scenario as a combustible material, only a very small number of studies found have looked at rehabilitation after a fire.

For increasingly large and expensive buildings, the ability to rehabilitate a building after a fire becomes financially important for insurance purposes.

When exposed to fire, mass timber forms a char layer which has no significant strength. Also a layer of uncharred timber has weakened and structural rehabilitation likely requires removal of at least a part of that layer. A method to rehabilitate fire exposed mass timber after a fire incident, could involve replacing the damaged layer with new material. This report discusses a case study where a portion of the ceiling of Test 5 of the compartment fire tests by Brandon *et al.* (2021) is repaired. The repaired specimen is structurally tested to failure to determine its structural capacity and flexural stiffness. Finally, comparisons with the mean capacity and stiffness values of the original CLT product will be made.

2 Aim

The rehabilitation exercise of this study aims to be applicable to the majority of floor elements. A typical span of CLT floor elements is roughly 5 m (~16 ft) for which the deflection requirements are generally governing the required structural dimensions. Depending on the load configuration and the regulations, for shorter than typical spans, the bending moment may be governing the performance. For short spans and exceptionally high loads the shear capacity becomes critical[1].

Therefore, achieving a floor element with a similar stiffness as the original floor element has the highest priority. A certain reduction of bending capacity and, more certainly, shear capacity is allowed by building regulations in most structures. The aims for the rehabilitation exercise therefore have distinct priorities:

---

[1] For the 5 x 35 mm (5 x 1 3/8 in) CLT, a characteristic bending capacity of 91.2 kNm/m (~20,500 lb*ft/ft) and a characteristic shear capacity of 173.25 kN/m (~11,870 lb/ft) can be calculated according to the manufacturer's European Technical Assessment. For CLT supported at both ends and an evenly distributed load, the shear capacity governs the structural performance if the span is shorter than 2.1 m. In that case a load on the floor of 165 kN/m^2 (~3,450 lb/sq.ft) would be needed to reach the characteristic shear strength, which is more than an order of magnitude higher than typically high floor loads.

1. The main aim of the rehabilitation work of this study is to fully recover the flexural stiffness of the CLT element.
2. The secondary aim of the rehabilitation work is to recover the bending capacity fully or to a large extent.
3. The tertiary aim is to recover the shear capacity to an extent that it is sufficient for the vast majority of floor structures.

3 Setup

Due to logistical reasons the reparation of a part of the ceiling could not take place directly after Test 5 by Brandon *et al.* Instead, a portion of the ceiling and part of a wall element (Figure 1) were relocated and positioned approximately 2.0 meters (6.6 ft) above the floor to simulate overhead onsite reparation (Figure 2). The dimensions of the ceiling slab were approximately 3.0 x 0.8 m (~9'10" x 2'7.5").

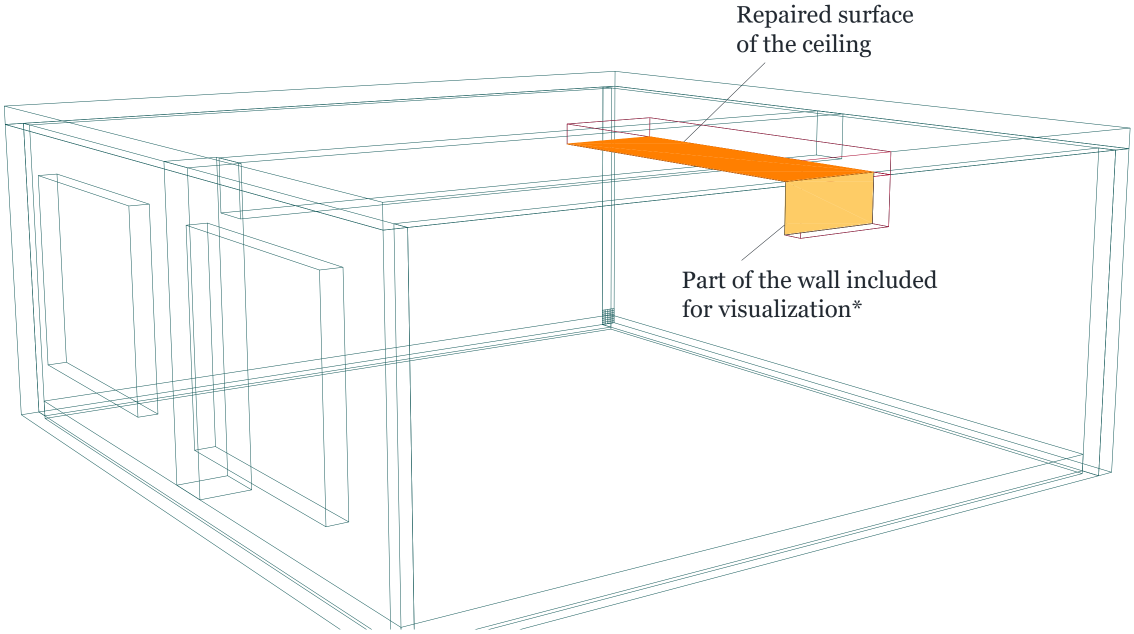


Figure 1: The original location of the specimen situated in the room of origin

** The wall was included to replicate a realistic scenario for repairing the ceiling in the corner and for visualizing the repaired intersection. However, the reparation of the wall section was not within the scope of this work. In contrast with the ceiling, planing of the charred wall surface was simply done with a handheld planer and the replacing lamella was screwed instead of glued.*

Figure 2: The specimen situated above the floor in the new working space. Note: the specimen was moved during the process, because of logistical reasons.

4 Method

The method implemented in the case study follows the following steps:

1. Mapping the thickness of the charred or damaged layer
2. Design and planning
3. Removal of the char layer
4. Planing of the surface including corners
5. Gluing procedure of replacing lamella
6. Finish the surface to meet architectural requirement

The methods chosen for each step for the current case study are discussed in the following sections.

4.1 Mapping the thickness of the charred or damaged layer

Before the reparation work is conducted it is required to have knowledge of the thickness of the char layer and the thickness of the layer that needs to be replaced. In addition, knowledge of the load bearing capacity of the structure during rehabilitation procedure is needed. To achieve a floor member with a similar load bearing capacity as the original structure, it is expected that removing the vast majority of char as well as some heat damaged timber is needed.

In this study it was chosen to use a resistograph[2], to determine the layer that needs to be removed (Figure 3). In most resistograph measurements there will be a relatively sharp drop of resistance, which has been used in multiple studies to identify the char depth (Brandon and Dagenais, 2018; Su *et al.*, 2018; Brandon *et al.*, 2021). Before the sharp drop of resistance there is often already a reduced resistance for some millimetres of drilling, providing a rough indication of the thickness of the heat affected layer.

Figure 3: Resistograph, drilling with a thin long drill through the ceiling to identify the thickness of the residual cross section.

---

[2] A displacement-controlled drilling machine able to log the resistance of a long thin drill and plot it over the distance.

The following was considered important for the use of a resistograph:

- Make sure the resistograph is held still while drilling, to avoid changing the friction.
- Eliminate drilling data through knots, which can be recognized by a significantly higher resistance in comparison with knotless timber. A potential drop after drilling through a knot can be caused by a transition from the knot to timber.
- Identify the lamella thickness and CLT lay-up. The density of the glued lamellas can differ and, in some cases, a sudden jump of resistance can be seen corresponding to the exact location where the drill head of the resistograph transitions between lamellas.

Figure 4 shows a resistograph measurements taken in the to be repaired section of the ceiling, giving an indication of the char depth and a rough indication of a heat affected layer. The average char depth in the ceiling was 50 mm (~2 in). However, it should be noted that there was some variability of char depth measured in the ceiling, as reported by Brandon *et al.* (2021), introducing some uncertainties.

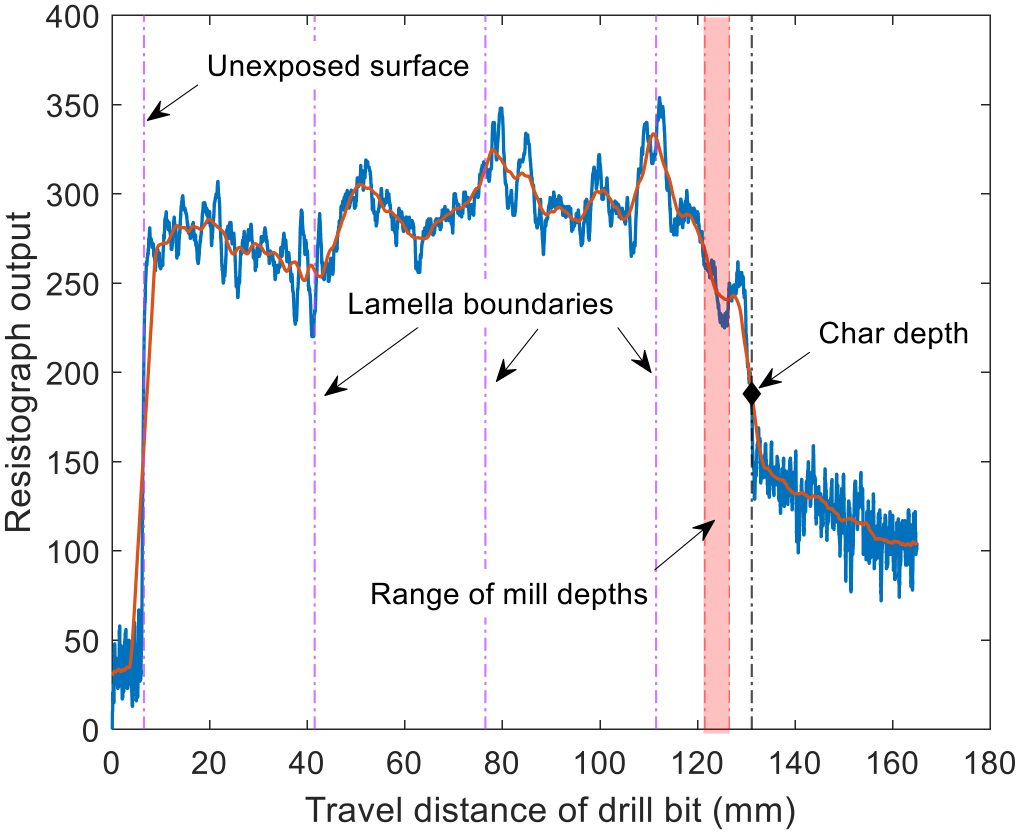


Figure 4: Resistance measured by the resistograph and an indication of the char depth and the milled depth. Note, the resistograph drill travels approximately 7 mm (0.28 in) before it reaches the unexposed surface. To calculate the depth from the exposed side, the drill bit travel distance minus 7 mm (0.28 in) should be subtracted from the original thickness of 175 mm (6.89 in).

4.2 Design and planning

4.2.1 Lay-up of rehabilitated CLT

As discussed in Chapter 2, the main aim of this exercise is to fully recover the flexural stiffness of the element. The secondary aim is to recover the majority of the bending capacity and the tertiary aim is to recover a significant share of the shear capacity. It was chosen to design for a high flexural stiffness and bending capacity by (1) replacing the charred lamellae with material of a higher strength grade and higher modulus of elasticity and (2) by changing the CLT layup whereby the lower lamella layer increases in thickness and the cross layer reduces in thickness for compensation.

Glued laminated timber beams of 66 x 315 mm (2.6 x 12.4 in), planed down to 60 x 315 mm (2.36 x 12.4 in) with a characteristic bending strength of 30 MPa (4350 psi; EN 14080:2013, class GL30h) were chosen for the material of the replacing lamella. The mean modulus of elasticity corresponding to the respective strength class is 13,600 MPa ($197 \cdot 10^4$ psi), which is higher than that of the original CLT product (12,000 MPa or $174 \cdot 10^4$ psi) given by the manufacturer. The glued laminated timber beams were oriented so that its face with the largest dimension was glued against the planed CLT.

To maintain the overall thickness of the floor slab, the cross layer needed to be planed down to approximately 15 ± 5 mm (0.6 ± 0.2 in) as shown in Figure 5. Thus, removing the exposed lamella entirely and 20 ± 5 mm (0.8 ± 0.2 in) of the cross layer. The indicated geometrical tolerance of 5 mm (0.2 in) is included to allow a planed surface that is not perfectly parallel to the CLT and to account for CLT that is not perfectly plane before the repair, while ensuring that the repaired specimen has at least the same dimension as the initial CLT. The tolerance for the flatness of the planed surface is significantly smaller as further discussed in the next sub-section. Based on the measurements of Section 4.1, removing the indicated layer was expected to be sufficient to remove the vast majority of charred material and leave some local heat affected wood in the slab. Since this remaining heat affected wood is in the cross layer and the cross layer does not contribute to the flexural stiffness and bending capacity, the heat affected wood is not expected to impact the bending capacity and the flexural stiffness. It can, however, impact the shear capacity. As indicated in Chapter 2, maintaining the full shear capacity is not important in general and it was decided to repair the specimen according to the lay-up of Figure 5

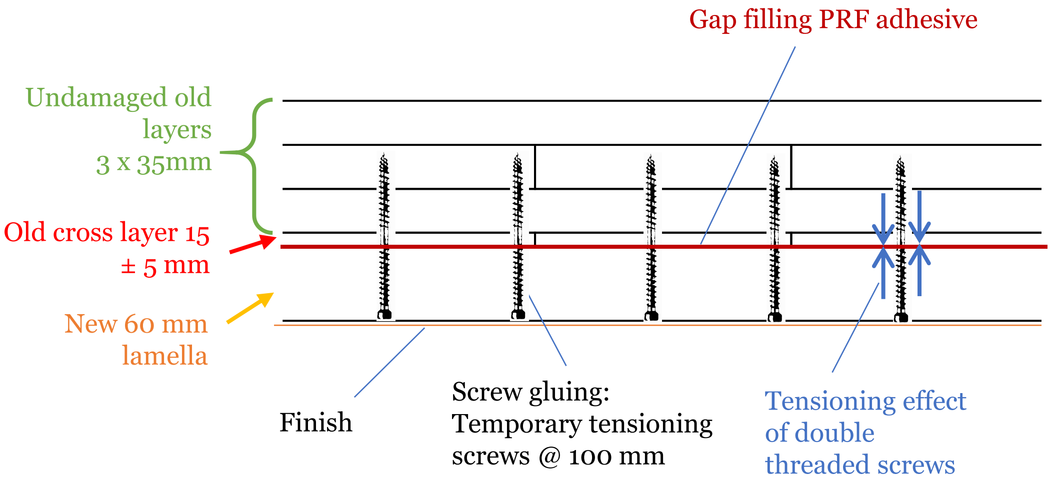


Figure 5: Lay-up of rehabilitated CLT

4.2.2 Choice of adhesive and compressing method

For onsite rehabilitation of charred mass timber, onsite planing of the charred surface would be needed. Although efforts are made to make the surface as plane as possible, larger imperfections should be expected for onsite planing compared to factory planing. Therefore, a suitable adhesive should be able to accommodate for larger imperfections than can be expected in factory planed timber.

It is also important to note that all stages of the gluing process for onsite gluing are relatively slow in comparison with factory gluing. Onsite gluing necessitates allowance for (a) a long pot life[3] (b) a practicable open assembly time[4] and (c) a long closed assembly time[5].

To accommodate for expected imperfections of the planed CLT and the expected time required for onsite assembly, it was chosen to use a gap filling PRF (Phenol Resorcinol Formaldehyde) adhesive[6]. The specific adhesive system used for this study, was graded to be effective for gaps up to 2 mm (~0.08 in) and for a glue line thicknesses up to 1.5 mm (~0.06 in) according to EN 14080:2013. The pot life, open assembly time and closed assembly time are dependent on the environmental conditions at which the gluing takes place and are provided in the technical data sheet of the adhesive system.

In addition to the ability for the adhesive to fill gaps and allow for time consuming gluing processes, it is important to use an adhesive with a high temperature performance to withstand a potential future fire without the occurrence of delamination. PRF adhesives historically showed good fire performance. As a result, design guides (Östman et al.

---

[3] The pot life is time that a glue mix can be used, starting from the moment the adhesive and hardener are mixed.
[4] Open assembly time is the time that elapses between application of the glue and assembly of the adherents.
[5] Closed assembly time is the time that elapses between assembly of the adherents and full application of the pressure.
[6] The gap filling PRF adhesive used was Prefere 4094 and hardener Prefere 5827, mixed according to instructions by the manufacturer (Dynea) at a ratio of 100:20 parts by weight.

2010) and standards (EN 1995-1-2:2004) have allowed to calculate the full strength of fire exposed timber that is glued using PRF adhesives. In the design of this case study, besides the choice of adhesive, implementing the new bond line deeper in the structure aims to ensure sufficient fire performance of the rehabilitated CLT.

A consequence of having a potentially increased bond line thickness as a result of imperfections of the planed surfaces, is an increased required compressing time. Therefore, it is essential to implement a compressing method that can apply pressure for an extended duration. Kurt (2003) showed that the bond line of screw glued members with a gap filling PRF adhesive can have similar or improved shear capacity in comparison with the bond line of press glued members with the same adhesive. For this case study, another advantage of screw gluing is that there is no additional compressing frame needed, which would need to have relatively large dimensions to be able to apply a reasonable pressure. For the reasons mentioned above it was chosen to implement screw gluing. To increase the pressure in the bond line, 6.5 mm (~0.26 in) diameter 130 mm (~5.12 in) long double threaded wood screws were used. The two 45 mm (1.58 in) long threaded parts at both ends of the screws had a different pitch, pulling the screwed members together and increasing the tension in the screw (Figure 5). The screws were implemented with approximately 100 mm (3.94 in) spacing in rows parallel to the grain. The distance between the rows was 100 mm (3.94 in).

To prevent heat conduction along the screws in a future fire, the screws were removed before the finishing layer was glued. A thin layer (3.6 mm / 0.14 inch plywood) was glued to the surface using a regular PVAC wood glue to obtain a surface of architectural grade.

4.3 Removal of the char layer

The char layer was removed firstly using a long handle scraper (Figure 6) and a drilling machine with steel brush attachment.

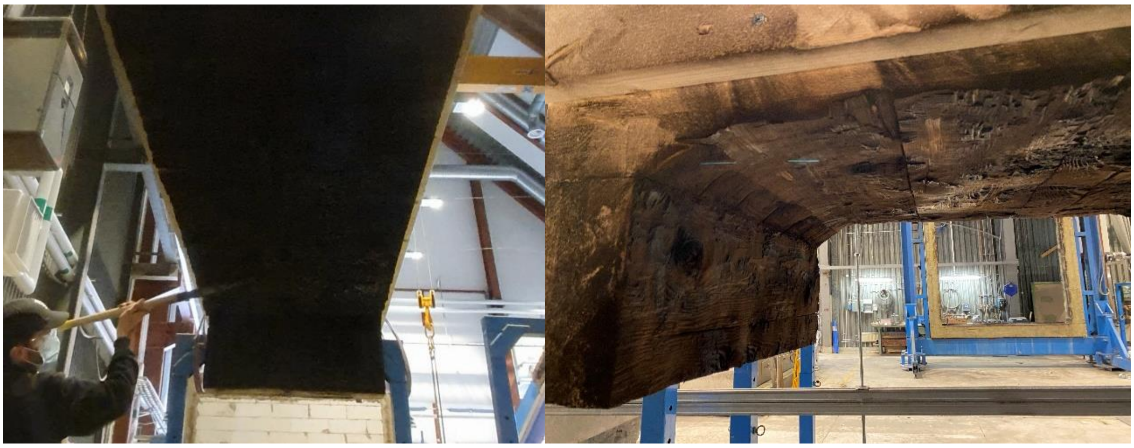


Figure 6: Removal of the char with a long-handled scraper (left) and surface after char removal (right)

4.4 Planing of the surface including corners

As the structure will remain in place during the rehabilitation work, planing equipment has to move past the surface. For this case study a sliding mechanism, with sliders in two directions was made. Two straight 82.6 mm (3 1/4 in) deep steel profiles (MQ-41 D-R, Hilti) were used for the longer slides and spanned approximately 3 meters. The shorter slides spanned approximately a meter and were made of two 41.3 mm (1 5/8 in) deep steel profiles (MQ-41-R), see Figure 7. The frame hung on rods which would need to go through screw holes in the floor made for the purpose of rehabilitation. Such holes would need to be fire sealed at the end of the work. PTFE spray was applied regularly to ensure low friction of the sliding mechanism. However, care was taken to avoid PTFE spray on the planed timber surface.

A battery charged router with a planing bit was used to plane the surface. This relatively light equipment will only subject relatively small forces to the frame and, therefore, avoids vibration issues. The surface was planed in four runs. For every run, the height of the planing bit was adjusted reducing the depth of the CLT panel by approximately 5 to 7 mm (0.2 to 0.3 in). For the final run only about 3 mm (0.1 in) was milled away to limit the vibrations in the frame and subsequently to reduce imperfections in the planed surface.

Figure 7: Planing of the charred surface with a router sliding on a frame (left and right)

Due to the geometry of the router used, it was not possible to plane the surface all the way to the intersection of the ceiling and the wall. To get as close as possible to the intersection, an angle grinder with a flap sanding disc was used to reduce the rounding in the corner (Figure 8). Approximately the last 12 cm (4 in) at the edge of the ceiling at the ceiling-wall intersection have been planed with a handheld planer that was especially made to plane wood until about 10 mm (0.4 in) to an inner corner (Figure 9). The last 10 mm (0.4 in) at the ceiling edge has been grinded down with an angle grinder.

Figure 8: Using an angle grinder with a flap sanding disc to reduce the corner rounding (left) to allow the router on the planing frame to come as close to the corner as possible (right).

Figure 9: Using a planer specialised in planing near inner corners (left) and assessing the planeness of the surface (right).

After planing, the planeness of the surface was assessed by holding a long straight level against it (Figure 10, Figure 11, Figure 12, Figure 13) and measuring the variability of the surface with a laser distance meter attached to the milling frame (Figure 14). The variability of the distance between the planed surface and the plane of the sliding frame was within 1 mm (~0.04 in), with exception of some locations with deeper charring and near the ceiling-wall corner. Near the ceiling wall corner, distance variations up to 2 mm (~0.08 in) were seen. The deepest identified gap was 8 mm (~0.31 in) which was at a location where the char depth exceeded the milled depth (Figure 14, right). Additional adhesive were applied at such locations as further discussed in Section 4.5.

Figure 10: Checking the planeness of the surfaces

Figure 11: Checking the planeness of the surface at the corner

Figure 12: Checking the planeness of the surface

Figure 13: Checking the planeness of the surface

Figure 14: Checking the planeness of the surface with laser distance meter

The planed surface contained some discolorations, which indicates that the materials in these locations are affected by heat and may have reduced material properties. As discussed before, this is only expected to influence the shear capacity which is generally acceptable to a relatively large extent. For structures with very high shear loads it is likely more appropriate to plane away all or nearly all discoloured material of a cross layer.

Figure 15: The planed surface photographed from below

The choices made in this project were based on the scale of the task. An automatic CNC machine could be made, which would increase the cost of equipment, but possibly reduces the overall costs for larger projects. Another alternative that could be considered, is to let the sliding mechanism stand on the floor of the rehabilitated compartment instead of hanging it on the ceiling.

4.5 Gluing of the replacing lamella

Before gluing, the location of the screws for screw gluing were marked on the new lamellas. Around 3 hours before the gluing process, the new lamellas were planed on the side where the glue was to be applied. The gap filling PRF adhesive used was Prefere 4094/5827 and the implemented ratio between the resin and the hardener was 100 to 20 parts by weight and is mixed in accordance with the manufacturers technical data sheet. The time elapsing between mixing of the application of the glue was at most 30 minutes and for the first lamella a separate batch was mixed. Using a glue comb, the glue was applied on the new lamella (Figure 16), which was located directly under the ceiling where it needed to be glued. In occasional remaining gaps of the planed surface of the CLT specimen the adhesive was also applied (Figure 17). A short open assembly time was achieved by gluing the lamellas in succession, only starting application of glue on the next lamella when the previous lamella was glued and the glue line was fully compressed with screws. Within 4 minutes after the onset of glue application the new lamella was assembled into position with three screws. The screwing of all remaining screws was done within 10 minutes. During the screwing with the double threaded screws, significant amounts of glue were pressed out. To avoid difficulties for gluing subsequent lamellas, the pressed-out glue was scraped off regularly. The duration of these processes was well within the ranges specified in the technical data sheet of the adhesive system.

In total approximately 4.0 kg (~9 lbs) of adhesive was applied (of which a significant share was squeezed out of the glue line during compressing) on the total surface of approximately 2.3 m^2 (25 sqft).

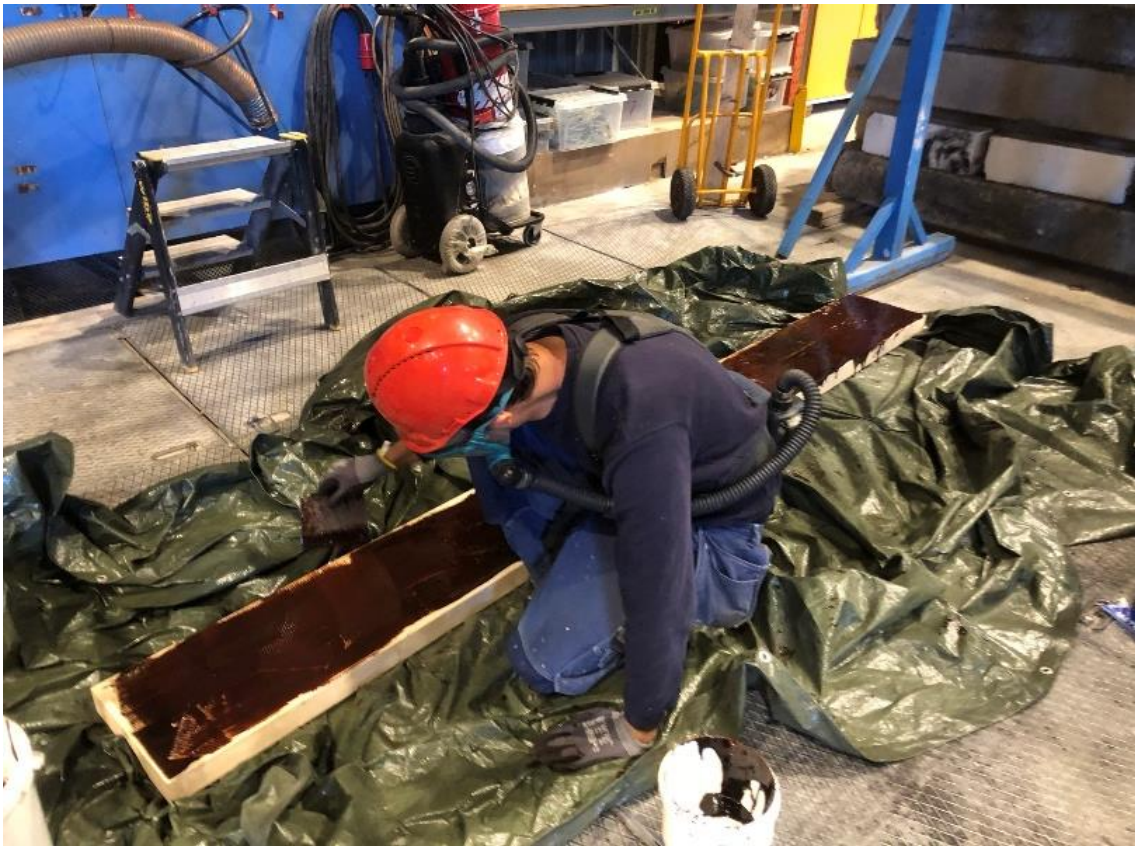


Figure 16: Applying adhesive on the lamella with a glue comb

Figure 17: Applying adhesive on the ceiling with a glue comb at the locations in the ceiling with deeper char depths than the milled depth

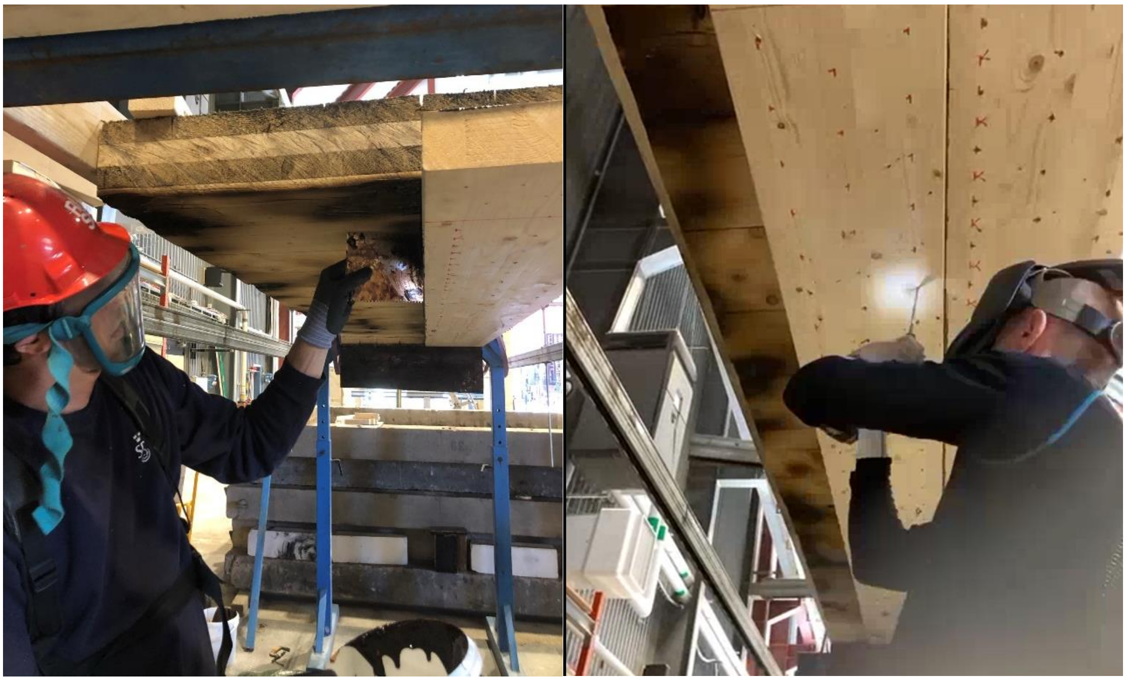


Figure 18: Scraping off pressed out glue (left) screw pressing (right)

4.6 Finish the surface to meet architectural standards

The surface of the repaired specimen was sanded, fire sealing was applied in the ceiling-wall joint, the screws for screw gluing were removed and a 3.6 mm (0.14 in) 3-layer plywood was glued to the surface using a panel lift to apply a small amount of pressure. The glue used was a regular PVAC wood glue. For this case study a large sheet of 2.4 x 0.9 m (7.9 x 3.0 ft) was glued and a smaller sheet of 0.4 x 0.9 m (1.3 x 3.0 ft) were glued.

The large sheet was larger than the surface with which pressure was applied. To prevent the edges from pealing some gypsum screws were used at the locations where pealing occurred. These screws were removed afterwards and the holes were filled and finished. It is expected that pins inserted with a pin nailer would be a better alternative as they are inserted more quickly and are practically invisible. The small sheet was glued on more easily as, with a similar compression force and a smaller surface area, the pressure was higher.

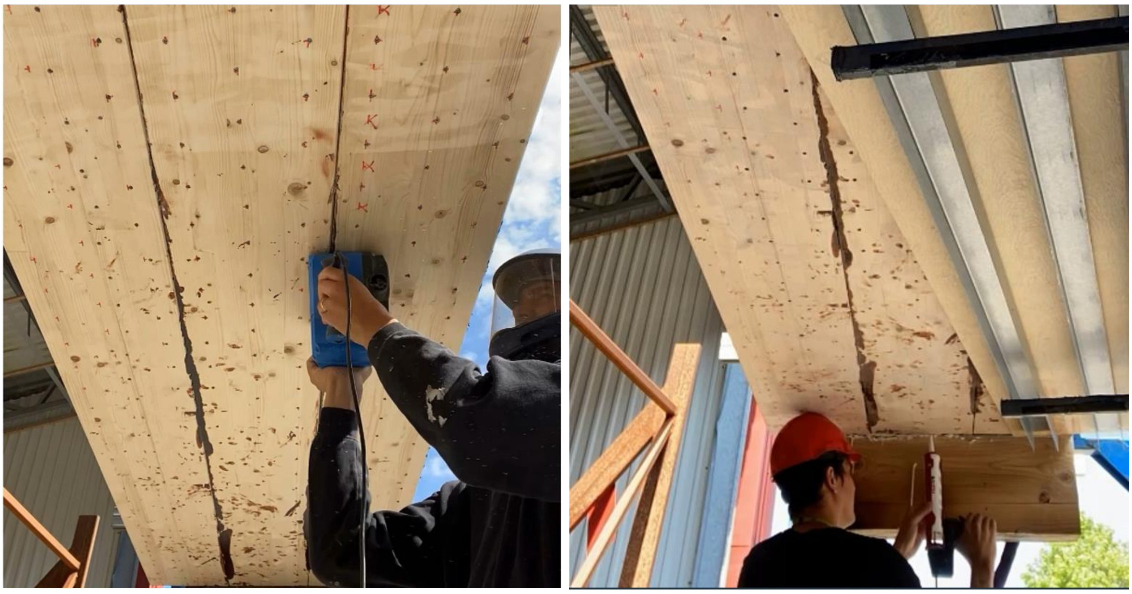


Figure 19: Sanding (left) and fire sealing the ceiling-wall joint (right)

Figure 20: Putting a small amount of pressure with a panel lift and moving the lift's position a few times with 5 minute time intervals to compress at different locations.

The finishing layer is included in this study to show a potential final result. A finishing layer, however, can be implemented in many ways, also with the help of companies that apply finishes to other structure types.

5 Observation of the specimen after rehabilitation work

Figures of the specimen after rehabilitation are shown in Figure 21 and Figure 22. Figure 23 shows a closeup of the ceiling joint, where the new ceiling lamella is structurally supported by the new wall lamella[7]. To achieve this the ceiling should be repaired prior to the wall.

Figure 21: Specimen after rehabilitation work

---

[7] Reparation of the wall was left out of the scope of this work. However, for demonstration of the configuration of the ceiling-wall connection after rehabilitation, a small part of the wall was restored in a simplified manner as discussed in Chapter 3.

Figure 22: Specimen after rehabilitation work

Figure 23: Ceiling-wall joint after rehabilitation work

After the rehabilitation process, a longitudinal cut was made splitting the ceiling in two long elements. In this cut the glue line thickness was between 0.1 and 0.2 mm (0.004-0.008 in) with exceptions of (1) a location where the char depth was higher than the depth that was milled away, and (2) approximately the last 120 mm (5 in) to the ceiling-wall corner. Figure 24, shows the bond line at a typical part of the longitudinal cross section. Figure 25 and Figure 26 show the longitudinal cross section at the corner joint and the location of deeper char, respectively. Near this corner, the glue line thickness varied between 0.4 and 1.4 mm (0.015-0.055 in). At the location of deeper charring, a length of approximately 90 mm (3.5 in) of the longitudinal section had an increased glue line thickness, exceeding 1.5 mm (0.06 in) for a total length of approximately 20 mm (0.8 in). The measurements in the longitudinal cross section, therefore, indicated that a gap filling adhesive graded for glue line thicknesses up to 1.5 mm (~0.06 in) was appropriate for this case study.

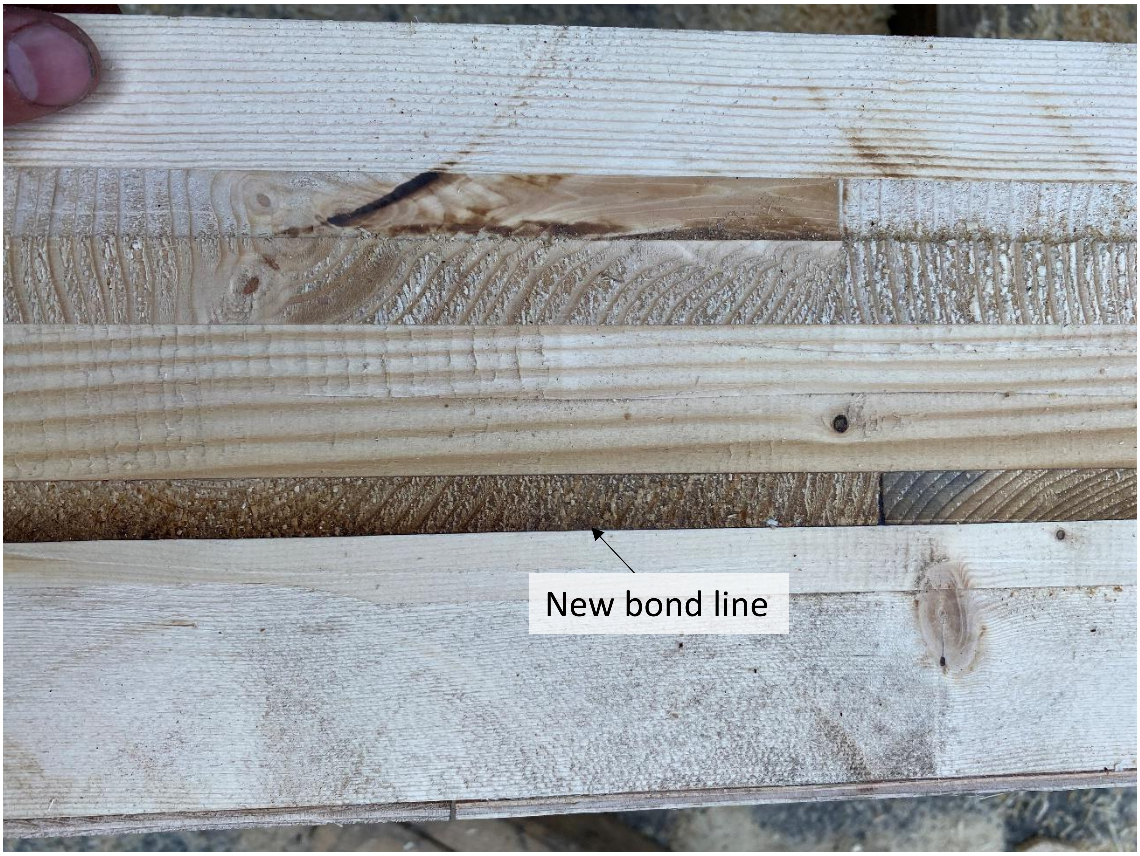


Figure 24: Photo of the longitudinal-section of the rehabilitated CLT member and an indication of the location of the PRF bond line

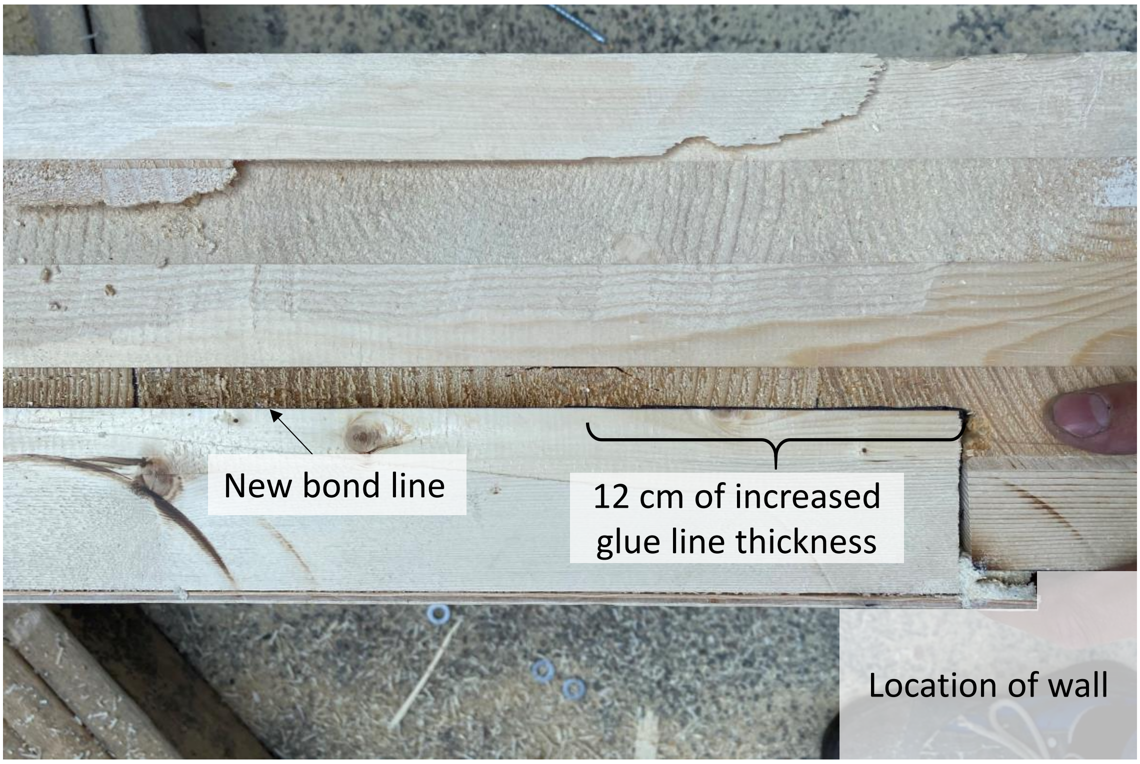


Figure 25: Photo of the longitudinal-section of the rehabilitated CLT member at the location of the ceiling wall joint, an indication of the location of the PRF bond line and an indication of the location of the wall

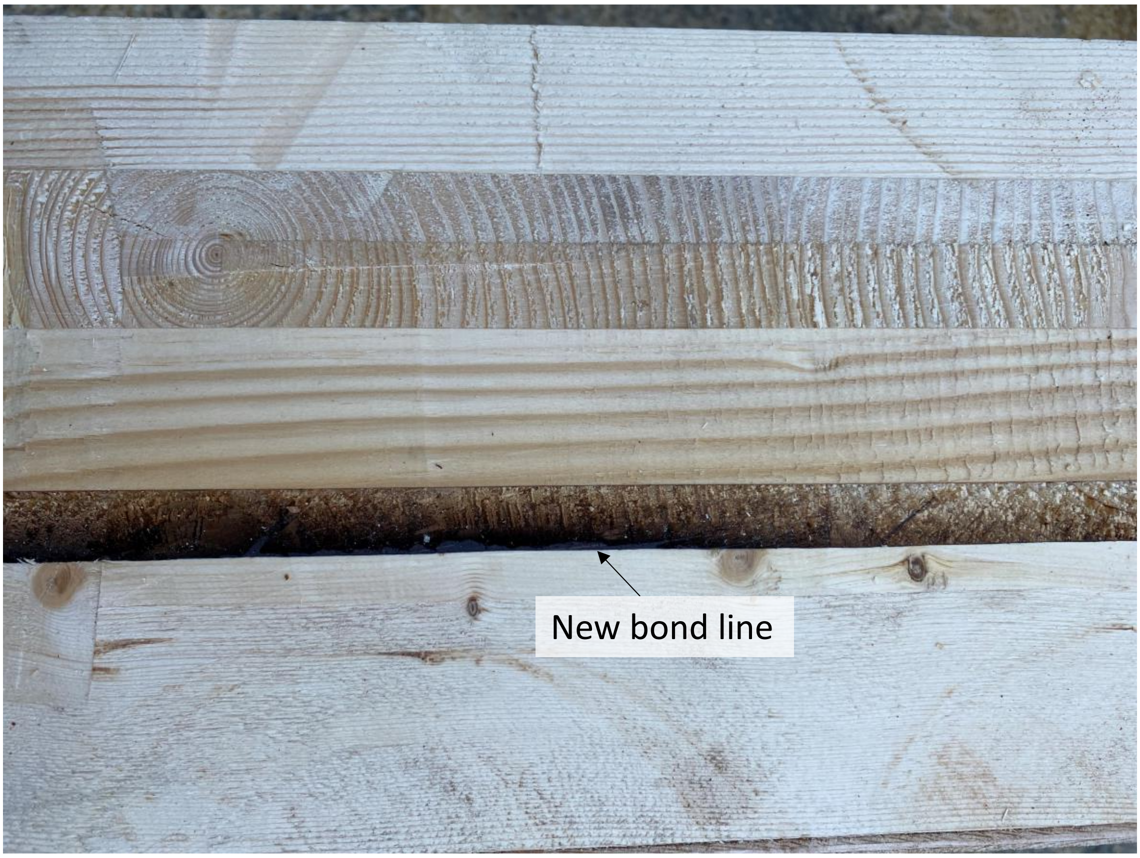


Figure 26: Photo of the longitudinal-section of the rehabilitated CLT member at the location where the char depth slightly exceeds the milled depth.

The total thickness of the specimen after rehabilitation varied slightly and the load bearing section of the slab was on average 8 mm (0.3 in) thicker than the original cross-section in the centre 860mm (34 in) of the slab. The finishing layer including adhesive added another 4.8 mm (0.19 in) to this difference. There are thinner veneer layers available for scenarios where the finishing layer is required to be thinner.

The lay-up of the final specimens for structural testing is shown in Table 1.

Table 1: Lay-up from top to bottom (average layer thicknesses at the centre cross section of the specimen)

Layer	Specimen 1		Specimen 2	
	Specimen width	Layer thickness	Specimen width	Layer thickness
5th CLT layer	386 mm (15.2 in)	35.0 mm (~1.38 in)	400 mm (15.7 in)	35.0 mm (~1.38 in)
Cross layer		35.0 mm (~1.38 in)		35.0 mm (~1.38 in)
3rd CLT layer		35.0 mm (~1.38 in)		35.0 mm (~1.38 in)
Cross layer		19.1 mm (~0.75 in)		16.9 mm (~0.67 in)
1st CLT layer, replaced lamella (parallel)		60 mm (~2.36 in)		60 mm (~2.36 in)
Thick glue line for finish PVAC		1.0 mm (~0.04 in)		1.0 mm (~0.04 in)
Plywood finish 3st lamella		1.6 mm (~0.06 in)		1.6 mm (~0.06 in)
Plywood finish cross lamella		1.6 mm (~0.06 in)		1.6 mm (~0.06 in)
Plywood finish 1st lamella		1.6 mm (~0.06 in)		1.6 mm (~0.06 in)

6 Structural testing

The specimen was cut longitudinally to create 2 specimens for structural testing. Two 4-point bending tests were performed according to EN 408:2010. It should be noted that the length of the available specimens was shorter than described by the standard, increasing the risk of shear failure during the tests. The total span was 2580 mm (~8.5 ft) with 860 mm (~2.8 ft) between the support and loading points and between the two loading points.

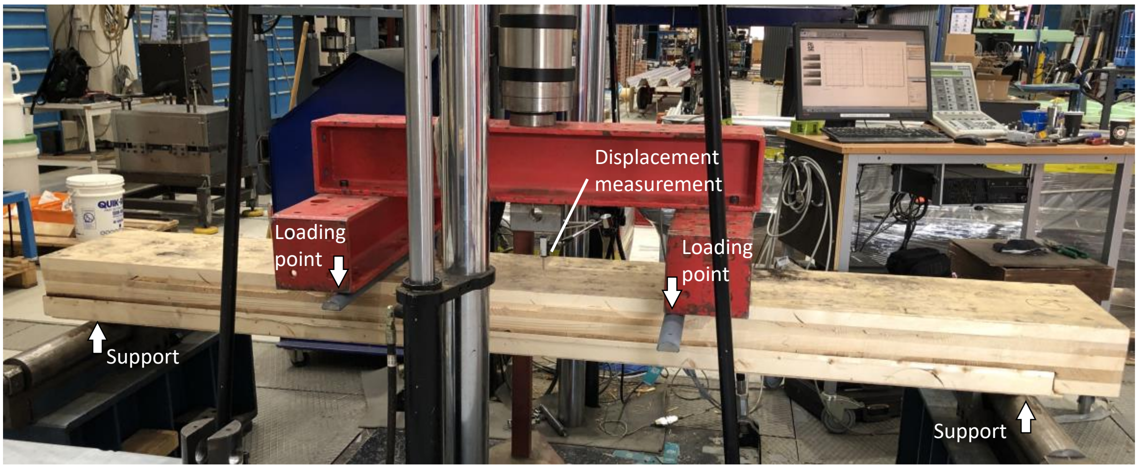


Figure 27: Bending test setup

Both specimens were tested to failure. The failure mode for both specimens was rolling shear failure in the lowest cross-layer (Figure 28). The failure occurred in material of the original CLT member. No signs of any failure were seen in the repaired part of the cross section, indicating sufficient performance of the new components (i.e. lower lamella and bond line) of the rehabilitated CLT. The failure loads were 112.0 kN (56.0 kN per load point) and 113.2 kN (25,180 lb and 25,400 lb).

Figure 28: Repaired specimen tested to failure. Shear failure occurred in the cross layer.

The relatively soft finishing layer was positioned on the 50 mm diameter dowel supports, which exhibited more dowel embedment deformation than expected. To eliminate the dowel embedment deformation from the specimen, the same specimen was subjected to embedment tests, close to the loading point of the bending test, to determine the relationship between load and embedment deformation. The average embedment stiffness (of both loading points), K, at the roll supports was 9,440 N/mm (53,900 lb/in) for Test 1 and 11,620 N/mm (66,400 lb/in) for Test 2, which was determined from the same load range as the specimen's modulus of elasticity. The embedment at the support introduces an uncertainty in the calculation of the modulus of elasticity, which is likely in the order of 10%.

The equation for determining the modulus of elasticity of EN408:2010 assumes homogeneous cross-section properties, which is not suitable for CLT, due to the presence of both parallel layers and cross-layers. Instead, the general Euler-Bernoulli beam equation for 4-point bending (first term), the shear deformation according to Timoshenko beam theory (second term) and a general elastic spring equation for the embedment deformation (third term) are used:

$$\Delta\delta_{center} = \frac{\Delta F a}{24EI} * (3L^2 - 4a^2) + \frac{\Delta F a}{kAG} + \frac{\Delta F}{K} \qquad \text{eq.1}$$

Where:

$$\Delta F = F_{0.4} - F_{0.1} \qquad \text{eq.2}$$

$F_{0.4}$ is 40% of the ultimate load per load point.

$F_{0.1}$ is 10% of the ultimate load per load point.

$$\Delta\delta_{center} = \Delta\delta_{0.4} - \Delta\delta_{0.1} \qquad \text{eq.3}$$

$\Delta\delta_{0.4}$ is the displacement that corresponds to 40% of the ultimate load determined from a linear regression for values between $F_{0.1}$ and $F_{0.4}$ with $R^2>0.99$.

$\Delta\delta_{0.1}$ is the displacement that corresponds to 10% of the ultimate load determined from a linear regression for values between $F_{0.1}$ and $F_{0.4}$ with $R^2>0.99$.

a is the distance between support and load point as indicated in Figure 29.

E is the modulus of elasticity

I is the second moment of area

L is the span between the supports as indicated in Figure 29.

K is the spring constant accounting for embedment at supports (N/m)

k is the shear coefficient, which is taken as k=5/6 for rectangular cross-sections

A is the cross-sectional area

G is the out of plane shear modulus.

Solving eq.1 to the modulus of elasticity leads to:

$$E = \frac{\Delta F a}{24I\left(\Delta\delta_{center} - \frac{\Delta F a}{kAG} - \frac{\Delta F}{K}\right)} * (3L^2 - 4a^2) \qquad \text{eq.4}$$

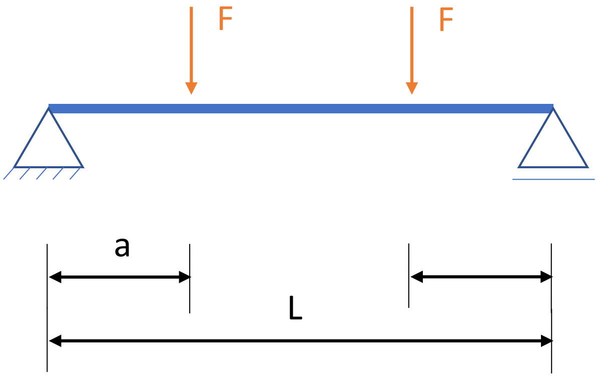


Figure 29: Load diagram for 4-point bending.

Eq.4 requires a shear modulus to determine the modulus of elasticity. The mean shear modulus for the original CLT member is 121 N/mm^2 according to the manufacturer. The mean shear modulus of the new lay-up calculated the same way by the manufacturer is 147 N/mm^2. It should be noted that there is some uncertainty regarding the real shear modulus as there is some heat affected wood in the lowest cross-layer as evidenced by some remaining discoloration and some reduction of resistance measured by the resistograph in the material that was not planed. However, not accounting for potential reduction of the shear modulus by heat would lead to an underestimation of the modulus of elasticity, which is conservative and, therefore still relevant. The results of the 4-point bending tests are summarized in Table 2.

Table 2: Overview of bending test results

Specimen	Width (mm)	Maximum load per load point (kN)	Modulus of elasticity (N/mm^2)	Bending capacity (kNm/m)	Shear capacity (kN/m)
1	386	56.0	18,395	>124.7*	145.0
2	400	56.6	11,693	>121.7*	141.5
Average	**393**	**56.3**	**15,044**	**>123.2***	**143.3**

* The specimen did not fail in bending. Therefore, the ultimate bending capacity is not known. It is however, known that the structure resisted the provided bending moment without failure.

Properties of the rehabilitated CLT are set against the mean and characteristic properties of the original CLT member, provided by KLH, the manufacturer of the original CLT. From the data it is concluded that the flexural stiffness increased with respect to the mean value provided by the manufacturer. The increased flexural stiffness is caused by a combination of (1) an increased modulus of elasticity, (2) change of CLT lay-up increasing the second moment of area of the parallel to grain lamella layers and (3) an increased thickness. A lay-up with equal thickness (60-10-35-35-35) and the modulus of elasticity determined from the tests would result in a flexural stiffness of 5730 kN^2/m, which also would exceed the mean value of the original CLT member.

The overview of Table 3 also indicates that the moment capacity of the rehabilitated member is at least close to the mean moment capacity of the original member. As the lay-up changed, increasing the section modulus, and the materials at the outer fibres (in the bottom and the top of the CLT slab) are undamaged, the ultimate moment capacity is expected to be higher than indicated in Table 3. However, due to the occurrence of shear failure, no ultimate value for the moment capacity was determined.

The shear capacity has reduced for the rehabilitated specimen as the shear capacity of the test specimens was 18% lower than the characteristic capacity of the original CLT. As rolling shear failure was observed in a layer that was visibly affected by heat, it is expected that the elevated temperatures have weakened the cross layer, which led to a reduction of shear capacity. Despite the reduction of shear capacity, the specimens showed a performance that is sufficient for most, practical applications for floors and is expected to only be critical for short floor spans in combination with exceptionally high loads[8].

---

[8] For the repaired CLT lay-up, supported at both ends and subjected to evenly distributed loads, the shear capacity governs the structural performance for floor spans under 3.5 m (11.5 ft). For floor spans shorter than 3.5 m (11.5 ft), the repaired floor would be able to bear loads more than 80 kN/m^2 (1670 psf) which is an order of magnitude higher than loads that would typically act on floors.

Table 3: 4-point bending test results in comparison with properties of the original CLT.

	Original CLT		Rehabilitated CLT	
	Characteristic value by the manufacturer (5th percentile)	Mean value estimated by manufacturer	Average of two tests after rehabilitation	Comparison between the rehabilitated specimens and the mean value by the manufacturer
Flexural stiffness (EI)		4240 kNm^2/m	6768 kNm^2/m	Increased
Modulus of Elasticity (parallel to grain members only)		12,000 N/mm^2	15,044 N/mm^2	Increased
Bending capacity	91.2 kNm/m	±125 kNm/m	>123 kNm/m*	Remained similar or increased
Shear capacity	173.25 kN/m	±200 kN/m**	143.3 kN/m	Decreased, with statistical significance

* The specimen did not fail in bending. Therefore, the ultimate bending capacity is not known. It is however, known that the structure resisted the provided bending moment without failure.

7 Conclusions

This report presents a case study of the repair of a section of a CLT ceiling after a significant fire. The specimen is obtained from a recent compartment fire test and is positioned and oriented in a way that is representative for onsite rehabilitation. The repair was done in six steps:

1. Mapping the thickness of the charred or damaged layer
2. Design and planning
3. Removal of the char layer
4. Planing of the surface including corners
5. Gluing procedure of replacing lamella
6. Finish the surface to meet architectural requirement

The method for determining the degree of damage, the method for planing the specimen, the adhesive type, the glue pressing methods were designed for the rehabilitation exercise. In addition, the layup of the CLT is changed to prioritise flexural stiffness and bending capacity over shear capacity, as they generally govern the structural capacity of CLT floors. The repair included the use of:

- a resistograph to identify the depth of the damaged layer;
- a milling frame to plane in combination with a router to plane the damaged surface;
- a gap filling PRF adhesive to perform structural gluing with an increased geometrical tolerance;
- screw gluing with double threaded tensioning screws to increase the pressure in the bond line in comparison to typical screw gluing.

After the six-step repair was done, the specimen was cut in half to perform two similar structural bending tests.

The results indicate that the flexural stiffness which generally governs the load capacity of floors, is increased by the rehabilitation work.

The results also indicate that bending capacity, which can govern for shorter than typical floor spans, is restored and possibly increased by the rehabilitation work.

The shear capacity of the repaired CLT was 18% lower than the characteristic shear capacity of the original CLT. Since shear capacity is only critical for short spans in combination with exceptionally high loads, this reduction has typically no effect in practical applications.

8 Future research

The following is recommended for future studies:

- A case study aiming to fully recover the shear capacity by including iterating step 4 of the six-step procedure of this study, until there is no discoloured material in the planed cross-section.
- Case studies of the rehabilitation of various of joints.
- A study of rehabilitation of CLT with high water damage
- A study of rehabilitation of CLT members with longer spans, to allow determining the ultimate moment capacity.

References

APA—The Engineered Wood Association. (2017). ANSI A190.1-2017: Standard for Wood Products-Structural Glued Laminated Timber.

APA—The Engineered Wood Association. (2018). ANSI/APA PRG 320: 2018: Standard for performance-rated cross-laminated timber. American National Standard. Tacoma, WA: APA-The Engineered Wood Association, 246.

Brandon, D. Sjöström, J. Hallberg, E., Temple, A. & Kahl, F. (2021), *Final project Report-Fire safe implementation of visible mass timber in tall buildings,* RISE Report 2021:40, RISE Research Institutes of Sweden, Borås. ISBN: 978-91-89385-26-9.

Brandon, D., & Dagenais, C. (2018). Fire Safety Challenges of Tall Wood Buildings–Phase 2: Task 5–Experimental Study of Delamination of Cross Laminated Timber (CLT) in Fire. National Fire Protection Association. NFPA report: FPRF-2018-05.

CEN (2013) EN 14080:2013 - Timber structures - Glued laminated timber and glued solid timber. European Committee for Standardization.

CEN (2005) EN 1995-1-2:2005 - Eurocode 5: Design of timber structures - Part 1-2: General - Structural fire design. European Committee for Standardization.

CEN (2010) EN 408:2010 - Timber Structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties. European Committee for Standardization.

Kurt, R. (2003). The strength of press-glued and screw-glued wood-plywood joints. Holz als Roh-und Werkstoff, 61(4), 269-272.

Östman, B., Mikkola, E., Stein, R., Frangi, A., König, J., Dhima, D., ... & Bregulla, J. (2010). Fire safety in timber buildings. Technical guideline for Europe. SP, 19.

Su, J., Leroux, P., Lafrance, P. S., Berzins, R., Gratton, K., Gibbs, E., & Weinfurter, M. (2018b). Fire testing of rooms with exposed wood surfaces in encapsulated mass timber construction. National Research Council of Canada, Ottawa.

RISE Research Institutes of Sweden AB
Box 857, 501 15 BORÅS, SWEDEN
Telephone: +46 10-516 50 00
E-mail: info@ri.se, Internet: www.ri.se

Fire Research
RISE Report 2021:67
ISBN: