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Repair of Fire-Damaged Mass Timber

A summary of assessment considerations and repair methods for post-fire conditions

While no one factor is responsible for the proliferation of buildings with exposed mass timber structural systems, the momentum—and innovation—we're seeing across the U.S. would not be possible without the inherent fire resistance of large wood members. During a fire, mass timber elements form a char layer on exposed surfaces while the portion of the core that remains relatively cool retains its structural strength, much the same as solid wood members in heavy timber buildings. It is this property of mass timber that allows the possibility of post-fire repair and reuse (as opposed to full replacement). But what happens *after* a fire? Clearly the char can't be left in place. How can a building be restored to its pre-fire condition?

Recognizing that repair of fire-damaged mass timber is a consideration for building owners and insurers, this paper answers common questions and summarizes four studies that discuss and/or investigate post-fire repair strategies. It is intended to better equip these audiences to accurately assess mass timber projects, including the risks and impacts of fire-damage remediation.

Confidence in Approaches and Schedules

Determining the true risks of a mass timber project requires an understanding of repair vs. replacement approaches, anticipated costs, and schedules. Without this knowledge, owners face unknown risks and insurance providers often assess higher premiums when insuring mass timber buildings.

Designed as a prototype for new sustainable building systems, Mississippi Workshop in Portland, Oregon is made from cross-laminated timber (CLT), which is a focus of research discussed in this paper. Waechter Architecture / KPFF Consulting Engineers

After a fire event in a mass timber building, common questions would include:

- Will the entire mass timber building have to be demolished and re-built?
- Can select mass timber elements be replaced in whole without having to demolish a substantial portion of the building?
- Is there a supply chain in place to provide replacement elements if necessary? How quickly would these elements be manufactured and delivered to the site?
- Can mass timber elements be repaired in place?
- What is the process for on-site assessment of fire-damaged mass timber to determine the extent of structural damage and whether repair or replacement are feasible options?
- Who is qualified to perform these assessments?
- What are the steps involved with on-site repair? Is temporary shoring needed?
- Can mass timber be repaired to as-built conditions regarding aesthetics, structural performance, and fire resistance, or will the application of new coatings or gypsum board coverings be necessary?
- What are the costs associated with on-site repairs?
- How long does on-site repair take?

These are unknowns today only because of the lack of fire events in completed mass timber buildings. While a few global examples exist, the U.S. has none at the time of writing. There are more than 800 commercial and multi-family mass timber projects built or under construction in this country,[1] and none have experienced significant construction phase or post-occupancy fire needing repair. This successful track record should not be overlooked. However, it does not answer the questions above, nor imply that there won't be examples in the future.

Assessing Degradation and Repairability

The formation of char is an effective means of protecting the core cross section of mass timber members (the section beyond the char zone and heat-affected zone). However, wood also degrades structurally when exposed to elevated temperatures, and this is key to evaluating the extent of damage and potential for repair. As noted in the USDA Forest Products Laboratory's (USDA FPL's) *Wood and Timber Assessment Manual*, Chapter 4, Post-Fire Assessment of Structural Wood Members,[2] "Sudden surface heating of a wood member in a fire results in surface charring and a steep temperature gradient. Thus, the stages of thermal wood degradation (discussed in the sidebar, The Science Behind Wood Charring) become zones of degradation in a structural wood member exposed to fire. In a broad sense, there is an outer char layer, a pyrolysis zone, a zone of elevated temperatures, and the cool interior (see Figure 1). These zones of degradation reflect the temperature profile through the cross section."

These degradations, as well as the effective char depths in various wood members, are accounted for in the calculations presented in Chapter 16 of the American Wood Council's (AWC's) National Design Specification® (NDS®) for Wood Construction and Chapter 3 of its Fire Design Specification for Wood Construction (FDS). The equations and data in these documents can be used to

Reduced Construction-Phase Fire Risks

Construction-phase risks associated with fire are different for mass timber buildings than with other framing systems.

Passive fire resistance – One of the main ways to demonstrate that a building will meet the required level of passive fire protection, regardless of structural material, is through FRRs of its elements and assemblies. Mass timber's inherent fire resistance gives it the ability to achieve 1- or 2-hour FRRs while remaining exposed for aesthetics. This means that a mass timber project has a certain level of passive fire resistance as soon as the frame is erected. Regardless of whether the design calls for additional protection over the mass timber member or assembly to achieve the required level of fire resistance, a certain level of fire resistance is inherent to the member or assembly itself, even without additional materials such as spray-applied fire proofing or gypsum wallboard.

Faster construction = less time for hazards to occur – A significant benefit of mass timber buildings is that they're typically built faster than buildings made from other materials. This also reduces the risk of fire, as less time under construction means less time for potential hazards such as hot work or arson. Because mass timber is prefabricated, there is very little on-site cutting or combustible construction waste.

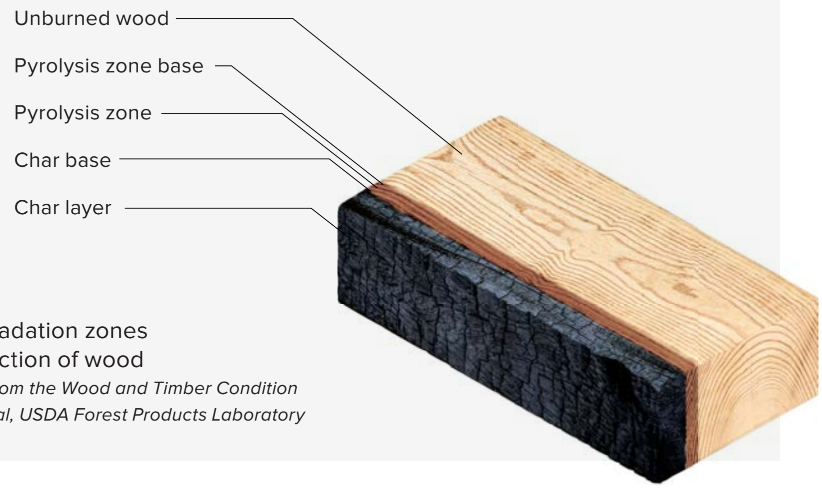

FIGURE 1: Degradation zones in a charred section of wood
Source: Adapted from the Wood and Timber Condition Assessment Manual, USDA Forest Products Laboratory

calculate the structural fire-resistance rating (FRR) of various exposed wood products, including solid sawn, glue-laminated timber (glulam), structural composite lumber (SCL), and cross-laminated timber (CLT). This method is recognized in Section 722.1 of the 2021 International Building Code (IBC) as a permissible means of demonstrating the fire resistance of exposed wood members and decking.

As noted by Douglas and Smart in *Structure* magazine,[3] "The design procedure allows calculation of the capacity of exposed wood members using basic wood engineering mechanics. Actual mechanical and physical properties of the wood are used, and member capacity is directly calculated for a given period of time—up to 2 hours. Section properties are computed using an effective char depth, a_{eff}, at a given time, t. Reductions of strength and stiffness of wood directly adjacent to the char layer are addressed by accelerating the char rate by 20%.

"Average member strength properties are approximated from existing accepted procedures used to calculate design properties. Finally, wood members are designed using accepted engineering procedures found in NDS for allowable stress design." A nominal char rate of 1.5 in./hour is given in NDS Chapter 16 and FDS Chapter 3, which is increased by 20% to achieve the effective char depth.

Assessing Fire-Damaged Mass Timber

There is no one-size-fits-all answer to the question of whether repair or replacement of fire-affected mass timber members will be necessary. It will depend on variables associated with the fire (how extensive it was, how long it lasted, whether sprinklers were activated, etc.) and those associated with the design of the building and mass timber members (was an FRR required for the members or were they only sized for structural needs, were they exposed or covered with gypsum board, etc.).

As such, it is recommended that a structural and/or forensic engineer be involved in the post-fire assessment of mass timber members.

As with fires in other building types, a site investigation would be needed to determine facts such as:

- Source of the fire
- Intensity and duration of the fire
- Growth pattern of the fire
- Whether the fire was extinguished prior to flashover, or flashover occurred

NFPA 921, Guide for Fire and Explosion Investigations, is the standard for performing post-fire investigations and is also relevant to mass timber buildings. Useful information can also be found in the *USDA FPL's*, Post-Fire Assessment of Structural Wood Members.[2] Among other valuable insights, this chapter notes the importance of establishing approximate temperature gradients and durations reached during the fire to better assess the structural degradation of the timber members.

> *For the post-fire assessment, the exposure of the structural wood members to elevated temperatures during the decay period of fire development should be considered. While temperatures are lower during the decay period, the duration of exposure can be prolonged compared with the duration of the fully developed post-flashover fire phase. The steep temperature gradient near the fire-exposed surface assumed in the normal assessment of residual load capacity is based on transient heating coupled with progressive charring of the wood cross section. During prolonged cooling, surface temperatures will decline while temperatures on the cool inside portion of the cross section will increase. Tests have indicated that this temperature increase in the interior of a wood member due to redistribution of heat after fire exposure*

Photo: David Barber, Arup

FIGURE 2: Glulam column before and after 2-hour fire test

is particularly the case for wood protected with gypsum board. Since the decay or post-extinguishment period is one of reduced temperatures, many damage observations made at the fire scene will be less helpful in determining the duration of the exposure. More careful and detailed inspections of structural members and connections will likely need to be done in a subsequent inspection when the general debris has been removed.

It is also helpful to obtain the original building drawings and/or calculations, to glean information on the following:

- Original mass timber member sizing, species, grades, layups, and connection details
- FRRs of the original mass timber elements
- Means of obtaining mass timber FRRs (e.g., inherent in the timber sizing demonstrated via calculations or tested assemblies, through the use of additional protection like gypsum wallboard, or a combination of both)
- Any modifications to mass timber members since the structure was built

One reason the original member sizing is important is shrinkage of the char zone. The thickness of the char layer post-fire is usually less than the depth of the char layer during the fire event; it may therefore be difficult to determine the original member sizes based only on evaluation of affected members.

There are multiple timber assessment methods available to site investigators, and one or more may be appropriate given the conditions of a project. Visual inspections are the most basic but are still effective as an initial assessment of damage. Other nondestructive methods, such as the use of a resistograph, can help determine the depth of damaged wood. This should include not only the char layer but also the heat-affected zone directly adjacent to it. In the research report, *Solutions for Upper Mid-Rise And High-Rise Mass Timber Construction: Rehabilitation of Mass Timber Following Fire and Sprinkler Activation*,[4] the following are noted as options for determining what the heat-affected zone could include:

For large timber members, it is common practice to neglect any impact to the heated zone when evaluating the residual capacity of fire-damaged members. This may not be conservative, and further reduction of the cross section may be more appropriate. In some guides, once the charred layer has been removed on heavy timber elements, additional removal of up to an additional 7.5 mm (0.3 in.) for compression members and 13 mm (1/2 in.) for tension members may be warranted. Some repair methods assume that a 30 mm (1.18 in.) layer of wood beneath the char is exposed to elevated temperatures and undergoes thermal degradation. In this method, the residual capacity of members is determined based on the residual depth of members plus the removal of an additional 30 mm (1.18 in.) of wood. Alternatively, when removing char, an additional 20% of the char depth of undamaged wood could be removed.

The Science Behind Wood Charring

It can be helpful to understand the thermomechanical degradation of wood when exposed to fire and elevated temperatures, as this explains why and how wood chars, and how this impacts its structural performance.

Chapter 18 of USDA FPL's *Wood Handbook* notes the following about wood pyrolysis:

> *As wood reaches elevated temperatures, the different chemical components undergo thermal degradation that affects wood performance. The extent of the changes depends on the temperature level and length of time under exposure conditions. At temperatures below 100 °C, permanent reductions in strength can occur, and its magnitude depends on moisture content, heating medium, exposure period, and species. Chemical bonds begin to break at temperatures above 100 °C and are manifested as carbohydrate weight losses of various types that increase with the temperature.*

The four temperature regimes of wood pyrolysis and corresponding pyrolysis kinetics are noted in the *Wood Handbook* as:

> *Between 100 and 200 °C, wood becomes dehydrated and generates water vapor and other noncombustible gases including CO_2, formic acid, acetic acid, and H_2O. With prolonged exposures at higher temperatures, wood can become charred. Exothermic oxidation reactions can occur because ambient air can diffuse into and react with the developing porous char residue.*
>
> *From 200 to 300 °C, some wood components begin to undergo significant pyrolysis and, in addition to gases listed above, significant amounts of CO and high-boiling-point tar are given off. The hemicelluloses and lignin components are pyrolyzed in the range of 200 to 300 °C and 225 to 450 °C, respectively. Much of the acetic acid liberated from wood pyrolysis is attributed to deactylation of hemicellulose. Dehydration reactions beginning around 200 °C are primarily responsible for pyrolysis of lignin and result in a high char yield for wood. Although the cellulose remains mostly unpyrolyzed, its thermal degradation can be accelerated in the presence of water, acids, and oxygen.*
>
> *As the temperature increases, the degree of polymerization of cellulose decreases further, free radicals appear and carbonyl, carboxyl, and hydroperoxide groups are formed. Overall pyrolysis reactions are endothermic due to decreasing dehydration and increasing CO formation from porous char reactions with H_2O and CO_2 with increasing temperature. During this "low-temperature pathway" of pyrolysis, the exothermic reactions of exposed char and volatiles with atmospheric oxygen are manifested as glowing combustion.*
>
> *The third temperature regime is from 300 to 450 °C because of the vigorous production of flammable volatiles. This begins with the significant depolymerization of cellulose in the range of 300 to 350 °C. Also around 300 °C, aliphatic side chains start splitting off from the aromatic ring in the lignin. Finally, the carbon-carbon linkage between lignin structural units is cleaved at 370 to 400 °C. The degradation reaction of lignin is an exothermic reaction, with peaks occurring between 225 and 450 °C; temperatures and amplitudes of these peaks depend on whether the samples were pyrolyzed under nitrogen or air. All wood components end their volatile emissions at around 450 °C. The presence of minerals and moisture within the wood tend to smear the separate pyrolysis processes of the major wood components. In this "high-temperature pathway," pyrolysis of wood results in overall low char residues of around 25% or less of the original dry weight. Many fire retardants work by shifting wood degradation to the "low-temperature pathway," which reduces the volatiles available for flaming combustion.*
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> *Above 450 °C, the remaining wood residue is an activated char that undergoes further degradation by being oxidized to CO_2, CO, and H_2O until only ashes remain. This is referred to as afterglow.*

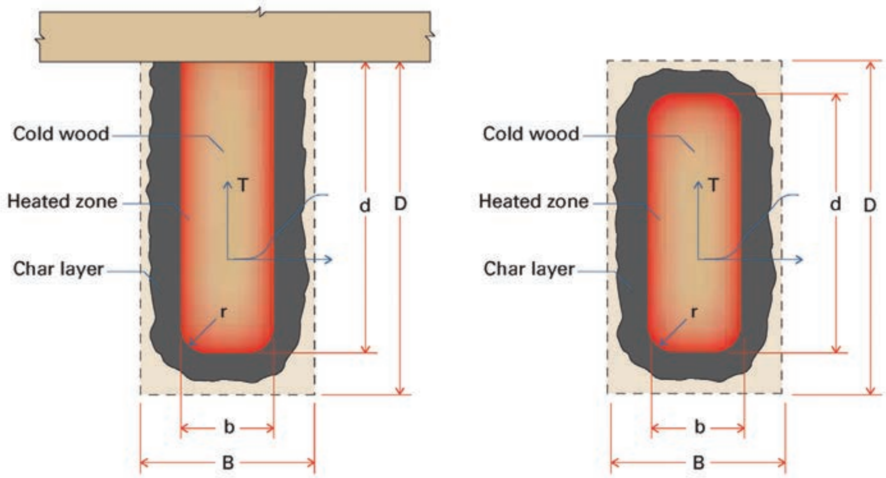


FIGURE 3: Reduction in member breadth and depth over time, t
Source: American Wood Council, Technical Report 10 – Calculating the Fire Resistance of Wood Members and Assemblies (TR 10)

This last point aligns with the information in Chapter 16 of the NDS and Chapter 3 of the FDS, which note that a nominal char rate of 1.5 in./hour is increased by an additional 20% when determining the residual structural properties of a fire-affected member:

> *Section 16.2.1.4 For structural calculations, section properties shall be calculated using standard equations for area, section modulus, and moment of inertia using the reduced cross-sectional dimensions. The dimensions are reduced by the effective char depth, a_{eff}, for each surface exposed to fire, where:*
>
> $a_{eff} = 1.2a_{char}$

The type of mass timber being assessed must also be considered. Some members are composed of parallel wood lamella laminated together, where the wide face would likely be exposed to a fire (e.g., a glulam beam). Some are composed of parallel wood lamella laminated together, where the narrow face would likely be exposed (e.g., an NLT floor panel). Some mass timber elements are made from layers of lamella in alternating directions, with a major and minor axis (e.g., a CLT floor panel). In the case of a glulam beam, if the char depth extends through two of the original lamella and the heat-affected zone extends partially into the third lamella, some or all of the third lamella should be removed and repaired (if appropriate). If the char depth in a fire-affected 5-ply CLT panel extends only through the lowest layer and the heat-affected zone extends partially into the second layer (commonly a minor axis layer) the question is whether some of the minor axis layer needs to be replaced. This is discussed further in the Research Institute of Sweden (RISE) repair work referenced in the next section.

The ultimate goal of on-site inspection and assessment is to evaluate the extent of fire damage. By understanding the depth of char and depth of wood with structural degradation, the dimensions of the remaining undamaged cross section can be determined. If this undamaged material, either on its own or in conjunction with structural repairs, can be shown to meet all of the original design criteria related to structural performance, fire resistance, and aesthetics, as well as other possible requirements, and considering the impacts of cost and schedule, the possibility of repair exists. If it is determined that the remaining, undamaged cross section is not adequate, even with repair, the damaged member(s) should be replaced.

Post-Fire Repair Studies

With few global examples of fire-affected mass timber structures, one way to assess post-fire repair is to look at repairs made after fire testing scenarios. There are also several studies with proposed repair methodologies.

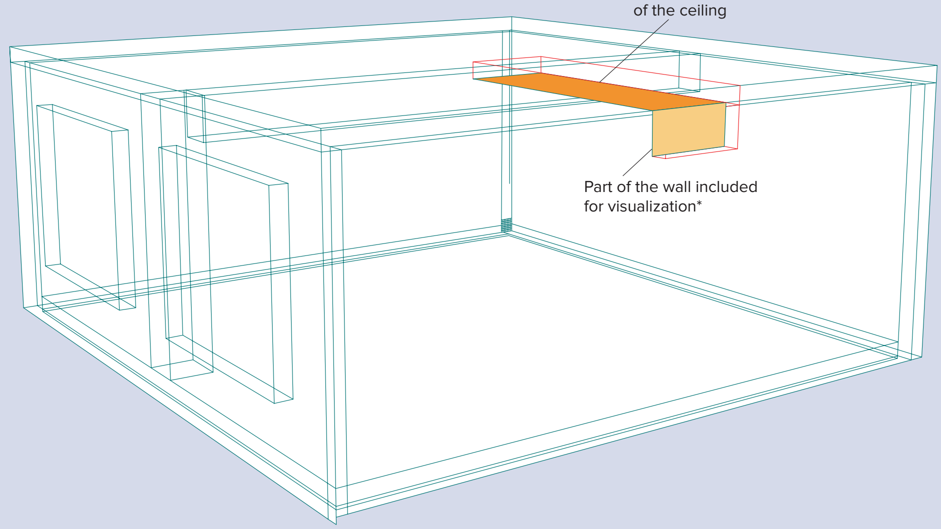
Post-Fire Rehabilitation of CLT – Research Institute of Sweden, 2021

In 2020, a series of five mass timber compartment fire tests were conducted at the Research Institute of Sweden (RISE). The main purpose of these tests was “to identify safe limits of exposed mass timber surface areas that correspond with performance criteria used for previous U.S. building code changes.”

Following the testing, one of the fire-affected CLT floor/ceiling panels was repaired to evaluate the repair process and assess the structural capacity of the repaired panel. The repaired panel was 5-ply, 6-7/8-in. thick with plan dimensions of 9-ft-10-in. x 2-ft-7.5-in. The panel was used in Test 5 of the testing program, which was a 4-hour compartment fire test. The fuel load density during this test was 560 MJ/m^2. The compartment dimensions were approximately 23-ft x 23-ft x 8-ft-10-in. (see Figure 4).

Repair of the CLT panel was done in six steps:

1. Map the thickness of the charred or damaged layer
2. Design and plan the repair
3. Remove the char layer
4. Plane the surface, including corners
5. Glue the new lamella to the panel
6. Finish the surface to meet architectural requirements



* *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 4: The original location of the specimen situated in the room of origin
Source: Post-Fire Rehabilitation of CLT, RISE Report 2021:67, Figure 1

FIGURE 5: Specimen situated on the floor in the new working space (moved for logistical reasons)
Source: Post-Fire Rehabilitation of CLT, RISE Report 2021:67, Figure 2

First, the research team took resistograph measurements of the entire compartment, a task that took about two hours to complete. Char depth was determined by drilling through the panel from the unaffected side; once the char zone was met, the tool indicated a sharp drop in resistance.

As noted in the repair report, “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.” When using a resistograph, reduced resistance for several millimeters of panel depth prior to the significant drop experienced at the char zone typically indicates the heat-affected zone.

The average char depth of the CLT panel was approximately 2 in. To remove all of the char zone and some of the heat-affected zone on the underside of the panel, all of the lowest layer was removed (1-3/8-in. thick in its original condition) along with just under 1 in. of the second layer.

The main tool used to remove char and heat-affected wood was a floor scraper with a long handle, supplemented by an electric screwdriver with a steel brush extension. (When doing this kind of work, proper personal protection equipment is critically important.) The next and most extensive step was planing. It took about 6 hours to plane the panel using a handheld router with battery and planer bit. In the corners, a handheld grinder and handheld planer were used, which allowed planing close to the edges. It is worth noting that, if planing a larger area of fire-affected mass timber, larger planing machines or perhaps an automatic computer numerical control (CNC) machine on rails would be worth looking into. All told, assembling the frame for planing, adjustments and leveling, and the planing itself, were done in one working day by one person.

The depth of affected wood removed included a tolerance of +/- 0.2 in., which meant the planed surface did not have to be perfectly parallel to the original condition. The actual planed dimensions should always be verified prior to installing the new lamella to ensure that the repaired specimen has at least the same dimension as the original CLT.

Once the charred and heat-affected wood was removed, the new lamella was prepared for installation. The method chosen for this repair was to replace the charred wood with material of a higher strength grade and higher modulus of elasticity. Additionally, while the removed wood included the entire lowest layer, which was oriented in the major axis, as well as a partial second layer oriented in the minor axis, this repair methodology used a single layer about equal in thickness to that of all the removed wood.

To create the replacement wood layer, 2.6 x 12.4-in. glulam beams were planed down to 2.36 x 12.4 in. The wide face of the glulam was oriented flat against the planed surface of the CLT, running parallel to the major axis of the panel (parallel to the original bottom layer). The planed surfaces were vacuumed to remove dust prior to glue application.

The new laminations were attached to the planed CLT with adhesive and screws. However, the screws were primarily used to attach the layer while the adhesive cured and were later removed. Prior to gluing, the locations of the screws were marked. This task, along with planing of the new layer, took about 40 minutes.

The team used a gap-filling PRF adhesive and hardener, mixed according to manufacturer instructions at a ratio of 100:20 parts by weight. They used 130 x 6.5 mm (5-in. x .25-in.) screws spaced 100 mm (4 in.) apart. The time required for curing depends on the glue-line thickness and ranges from a few hours to a day (per the manufacturer’s technical sheet). For the glue-line thickness used, the cure time on this repair was approximately 10 hours. Due to the pot life of the adhesive, it was imperative to work fast. Within four minutes of the adhesive application, each new lamella was assembled into position with three screws, and the remaining screws were installed within 10 minutes. Ventilated conditions and proper personal protective equipment are important during this stage.

Once the adhesive cured, the screws were removed, the surface of the new lamella was sanded, and 0.14-in.-thick plywood was glued to the surface of the new lamella using PVAC wood glue and applied pressure from a panel lift. The plywood layer was intended to show one option for final repair aesthetics. Another option would be to leave the new lamella exposed as the final finish.

In total, the repair took about two and a half days for all manual work other than finishing, which was completed at a later date. The time spent on a per square foot basis would likely decrease when larger surface areas are being repaired.

The cost of the repair work was assessed by Seagate Mass Timber using a description of the repair methods, materials and time involved provided by the repair facility. One significant expense was the cost of the resistograph, nearly $14,000 USD. This device would typically be owned by the firm performing the on-site investigation and wouldn't be included in repair costs. It was estimated that the time involved in evaluating the extent of damage using the resistograph and designing the repairs was 6 hours—which, at a rate of $75/hour, equates to $450.

The time involved in repair was estimated to be 42 hours (21 hours x 2 people). At a rate of $75/hour, this equates to $6,300 in labor. Materials associated with the repair (obtained in August 2022) were estimated to cost approximately $4,500. Accounting for additional 20% overhead and 20% markups for labor, as well as 10% overhead and 10% markups for materials, the total cost of repair work, not including damage evaluation, was estimated to be $14,205. As with time spent, the cost of repair work on a per square foot basis would likely be significantly reduced when a larger area is being repaired. As noted above, these cost estimates include several assumptions that would need to be verified on a per project basis.

After the finish work was completed, the repaired specimen was cut longitudinally to create two long, narrow panels. Four-point bending tests were performed on the panel to assess its structural capacity, following the protocols of the European Standard, EN 408:2010. The panel span was approximately 8-ft-6-in. with three equal spacings of about 2-ft-10-in. between support and loading points, and between the two loading points. Note that this panel length/span is shorter than what is prescribed by the EN standard, which would increase the impacts of shear on the test.

Both panels were tested to failure. In both specimens, the failure mode noted was rolling shear in the lowest cross layer (part of the original CLT panel, not the new lamella). No signs of failure were noted in the new lamella. The shear capacity of the repaired panel was 18% lower than the original. As noted in the RISE report, "As rolling shear failure was observed in a layer that was visibly affected by heat [the remaining thickness of the lowest cross layer], it is expected that the elevated temperatures have weakened the cross layer, which led to a reduction of shear capacity." The RISE report also points out that for most typical mass timber floor panel spans and loading conditions, shear is not the controlling design criteria and it is very possible that the repaired panel, with an 18% reduction in shear capacity, is still adequate for the given structural conditions. In rare instances where shear is the controlling design criteria, it may be necessary for more material to be removed during planing, thereby ensuring that all thermally-degraded material has been removed.

The moment capacity of the repaired panel was not determined since it could not be tested to bending failure due to shear failure occurring first. However, the bending capacity of the repaired panel at the time of rolling shear failure was noted and was close to the mean moment capacity of the original member. Due to the use of a thicker and higher-grade repair lamella, compared to the original bottom layer, it is likely that the actual bending capacity is higher than that shown in Table 1.

For additional information, read the RISE report of the repair work and findings, *Post-Fire Rehabilitation of CLT,*[5] or watch the video summarizing this work.[6] The full report of the RISE fire testing, *Fire Safe Implementation of Visible Mass Timber in Tall Buildings – Compartment Fire Testing*, is also available.[7]

TABLE 1: 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.*

Source: Post-Fire Rehabilitation of CLT. RISE Report 2021:67, Table 2

The RISE work described above should not be viewed as a universal repair solution, nor should all fires be expected to produce the same damage to timber members. This data is useful for demonstrating one viable method of repair as well as the associated timeline and costs. However, as more mass timber projects are built, and more research is undertaken, new repair methodologies will be conceived and tested. For example, the RISE report suggests potential research to investigate methods of repair that result in restoration of full shear capacity, and repair of water damaged CLT.

Structural Repair of Fire-Damaged Glulam Timber – ASCE, 2020

This work included the fire testing, repair and structural testing of two exposed glulam members and two glulam members covered with one layer of Type X gypsum wallboard. Two reference glulam members, which were not subject to fire exposure, were also evaluated for comparison. The glulam members were Douglas fir, 16c-E stress grade per the National Lumber Grades Authority (NLGA) grading rules, laminated with melamine-formaldehyde adhesive. One item noted in the report was that this stress grade is typically used in compression members. However, bending tests were performed on the repaired members to determine their capacity. Cross sectional dimensions of members 1, 3 and 5 were 6-7/8-in. x 7-1/2-in. while members 2, 4 and 6 were 6-7/8-in. x 9-in. All six members were 8-ft-4-in. long.

Information on the fire test protocol is documented in the report, *Performance of Type X Gypsum Board on Timber to Non-Standard Fire Exposure*.[8]

The depth of fire-affected wood removed ranged from approximately 0.5 in. to 1 in. across the four samples. The length of fire-affected wood along the encapsulated samples was about 21 in. and along the exposed samples about 44 in. A saw set to a specific cut depth was used to create boundaries for wood removal, and most of the wood within these areas was removed with a chisel. A belt sander was then used to create a smooth and uniform surface to the depth required. This work was based on visual observations only, mainly discoloration of the wood.

With the affected wood removed, new laminates of the same species and equivalent grade as the original members were installed. The laminates were cut and planed to match the depth of the wood removed and bring the member back to its original dimensions. Most of the new laminates were installed with 5/16-in.-diameter x 6-in.-long screws. However, the bottom laminates on samples 4 and 6 were installed with 3/4-in.-diameter x 8-in. screws to meet the required penetration depth. No adhesive was used to attach the new laminates to the existing member.

The repaired members were structurally tested using four-point bending tests following a modified procedure from ASTM D 143-14 – Standard Test Methods for Small Clear Specimens of Timber. Each member was tested six times. After char removal but before installation of the new laminates (a condition the report calls the carved members), each sample was tested three times at a load much lower than its ultimate capacity. After repairs were complete, each sample was tested three additional times at the same load. The intent of initially using the low testing load, which theoretically corresponded to the load resulting in members reaching their deflection limit, was to evaluate the stiffness of the members in a serviceability limit state. However, resulting deflections were less than those calculated and another round of testing using a higher load was performed. The magnitude of the higher load was determined experimentally and was less than half the strength capacity of each member. After the six loading and unloading cycles were complete, each sample was loaded until failure.

According to the report, the repaired members were not able to withstand the same amount of load as the control members (approximately 49%-66%). However, the repaired members could withstand more than twice the force calculated for the original glulam members based on the standard, CSA 086-14. Since these calculations would have been the basis of design for a typical glulam member in a non-fire scenario, rather than the actual tested capacity of the control members, it could be said that the repaired members achieved the original design loading capacity. However, the repair did not restore the actual loading capacity. It is also worth noting that the new laminates were butt jointed with the existing laminates (i.e., no scarf joints) and the repaired members had up to 35% higher stiffness than the carved members. In one instance, the stiffness of the repaired member was higher than that of the control member.

The report recommends further research into methods of obtaining composite action between new laminates and remaining cross sections by varying the length and/or depth of char removed (beyond just the char zone), as well as the type, spacing and penetration depth of screws used to attach the new laminates. It also suggests that the effects of creep on loaded members during a fire should be investigated further, and a greater understanding of the thermomechanical degradation of engineered timber is necessary.

Additionally, while size and other characteristics of an original cross section can be achieved with a repaired member, the fire performance may not be equivalent. Other topics for investigation include the effects of screws used to attach a new laminate to an existing carved section, which could conduct heat into the wood, and the potential advancement of a fire into the gaps where a new laminate butts an existing section.

The concepts developed in this repair strategy were applied to a hypothetical case study to estimate the cost of performing such repairs on a real structure. Specifically, the case study assumed the use of glulam columns matching the species and stress grade of those in the repaired members, with column dimensions of approximately 16-1/4 in. x 16-1/4 in. x 9-ft-10-in. tall. Columns were assumed to be exposed to fire on all four sides, and each floor plate had 80 glulam columns.

Nine fire scenarios were analyzed—one column, eight columns, or all 80 columns affected by fire, and each condition experiencing a 30-minute, 1-hour and 2-hour fire. Depths of char and heat-affected zones were calculated using CSA 086-14 (0.7 mm/minute, which is about equal to 1.65 in./hour).

The cost estimates (which are in 2019 Canadian dollars, do not include taxes, and assume a building in Toronto, Ontario) account for engineering, materials, and repair/installation labor. Other costs noted in the report, which may need to be considered but were not part of the case study, include temporary support of column loads, cleaning and repair of smoke damage, repair of other fire-affected timber members such as glulam beams and CLT floor panels, and loss of revenue if the building needs to be partially or wholly unoccupied during repair work.

The total repair cost of a single glulam column was estimated to be $2,121.63 for a 30-minute non-standard fire exposure, $2,449.99 for a 1-hour non-standard fire exposure, and $3,226.61 for a 2-hour non-standard fire exposure. Estimates for the other six fire scenarios are presented in the reference report. The report also notes that, in some instances, column replacement may be more cost-effective than repair, particularly with deeper char and more extensive repair work.

Extrapolating these repair costs, the following unit cost of repair per in. of affected wood thickness can be calculated:

Surface area of affected column = (16.25 in.(1 ft/12 in.)(4 exposed surfaces)(9-ft-10-in.) = 53.3 sqft

- 30-minute fire = 0.83 in. char depth
  - Cost = $2,121.63/(53.3 sqft) = $39.81 per square foot of repair area (repair area = surface area of glulam column being repaired)
- 1-hour fire = 1.65 in. char depth
  - Cost = $2,449.99/(53.3 sqft) = $45.97 per square foot of repair area
- 2-hour fire = 3.3 in. char depth
  - Cost = $3,226.61/(53.3 sqft) = $60.54 per square foot of repair area

These unit costs may be helpful in assessing the total cost of a fire repair. For example, after an initial post-fire assessment is completed, the average depth of char can be determined along with the total surface area of timber to be repaired. These two variables can then be used to estimate the total cost of repairs.

A full report of the assessment, repairs, and cost study can be found in the report, *Structural Repair of Fire-Damaged Glulam Timber.*[9]

Post-Fire Restoration of Cross-Laminated Timber (CLT) – SmartLam and American Wood Council, 2018

In 2017, a series of five mass timber compartment fire tests was conducted at the U.S. Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory. These tests were designed by the International Code Council's Ad Hoc Committee on Tall Wood Buildings and managed by AWC and USDA FPL. The purpose was to observe the performance of a two-level apartment-style structure built from mass timber. Each level consisted of a one-bedroom apartment, an L-shaped corridor, and a stairwell connecting the two levels. A key variable was the amount and location of exposed mass timber, with the surface area protected by gypsum wallboard ranging from 100% to none.

It was partly the results of these tests that led to significant changes in the 2021 IBC—namely the creation of three new construction types that allow mass timber structures up to nine, 12 and 18 stories (respectively). During the code change review process, the question of how exposed mass timber buildings would be repaired in the event of a fire was raised. In response, CLT manufacturer SmartLam and AWC developed a set of repair methodologies based on the fire-affected mass timber members from the ATF testing.

Five rehabilitation methods, including calculations and sketches, were established in theory. However, they were not physically carried out and tested.

One difference between the ATF repair theories and repairs undertaken following the RISE fire tests was the amount of exposed timber and resulting extent of fire-damaged CLT. The ATF fire tests included isolated areas of exposed CLT ceiling, while the RISE tests had full exposure. As such, the RISE repairs consisted of removing and installing new lamella that essentially covered the entire underside of the CLT panels. The ATF repair designs involved new lamella in only a portion of the CLT panels, part way across their span. As such, these repair designs called for structural splicing of the new lamella into the existing lamella to achieve the intended structural benefits.

The five repair options developed based on the ATF tests were:

1. Removal and replacement of damaged CLT panels
2. Analysis to prove fire-damaged CLT has capacity to meet demands of service loads
3. Char removal and new lamella installation with fasteners and/or adhesive to restore full capacity of CLT
4. Char removal and new lamella installation with mechanical splices to restore full capacity of CLT
5. Char removal and new lamella installation with embedded plates to restore full capacity of CLT

FIGURE 6: Fire-affected CLT panels from the ATF fire testing
Source: USDA Forest Products Laboratory

Option 1 was simply to remove all fire-affected mass timber members and replace them in whole. The complexity of this approach in a completed building vs. a building under construction would need to be evaluated. While this repair option may be necessary in some instances, in situ repair could be more efficient and economical, and should be explored prior to advancing to full element repair.

Option 2 would require removal of all fire-damaged wood and installation of new lamella to restore the repaired CLT panels to their original thickness. The replacement lamellas would not be structurally spliced with the remaining panels (they'd be attached with fasteners and/or adhesive); therefore, this approach would not restore the panels to their original structural capacity. In this option, a butt joint would be used to connect new and existing lamella. This would permit the new lamella to be exposed, meeting the original design for aesthetics. It would also restore the FRR of the original panel.

Option 3 would require removal of all fire-damaged wood and installation of new lamella to restore the CLT panels to their original thickness. In this option, scarf joints would be used to splice the replacement lamellas with the existing bottom lamella to create structural continuity and restore the panels to their original structural capacity. The new lamella would be attached to the existing lamella with fasteners and/or adhesive.

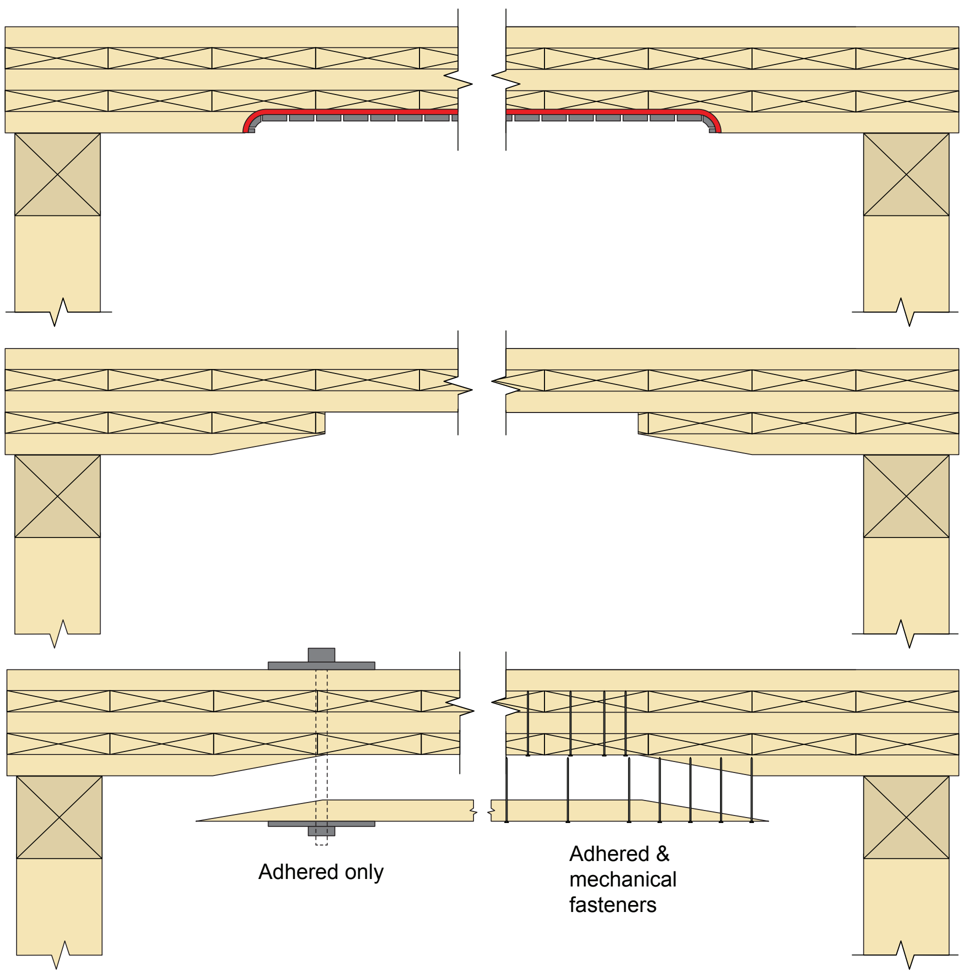


FIGURE 7: Option 3 repair strategy
Source: SmartLam and American Wood Council (adapted)

TABLE 2: Summary of repair options in the SmartLam/AWC study

	Restores Structural Capacity	Restores Fire-Resistance Rating	Restores Exposed Timber Aesthetic
Option 1	Yes	Yes	Yes
Option 2	No	Yes	Yes
Option 3	Yes	Yes	Yes
Option 4	Yes	Yes	No
Option 5	Yes	Yes	No

Option 4 would require removal of all fire-damaged wood and installation of new lamella to restore the repaired CLT panels to their original thickness. Similar to Option 2, butt joints would be used at interfaces between new and existing lamella. However, 3/16-in.-thick x 2-in.-wide steel plates with inclined screws would be used to mechanically splice the underside of the new lamella to the underside of the existing lamella. This would allow the panels to be restored to their original structural capacity. Due to the aesthetic impacts of the new steel splice plates, it would be necessary to install a 5/8-in. Type X gypsum wallboard ceiling under the panels.

Option 5 would require removal of all fire-damaged wood and installation of new lamella to restore the repaired CLT panels to their original thickness. Similar to Option 4, butt joints would be used at interfaces between new and existing lamella. However, instead of steel splice plates, this option includes vertically-oriented plates embedded in the wood. Based on the HBV shear connector system or similar, these plates would be saw cut into the underside of the existing panel and extend into the new lamella. Adhesive or epoxy would be used to bond the embedded plates to the existing and new lamella to create a timber-timber composite system, thereby restoring the panel to its original structural capacity. Because the embedded plates and saw would affect both the fire resistance and aesthetics of the repaired section, it would be necessary to install a 5/8-in. Type X gypsum wallboard ceiling under the panels.

For a summary of the five options, see Table 2.

For detailed information on these repair strategies, read the report, *Post-Fire Restoration of Cross-Laminated Timber (CLT)*.[10] A full report of the ATF fire testing, *Compartment Fire Testing of a Two-Story Mass Timber Building*, is also available.[11]

Solutions for Upper Mid-Rise and High-Rise Mass Timber Construction, Rehabilitation of Mass Timber Following Fire and Sprinkler Activation – FPInnovations, 2019[12]

This report provides an assessment and collection of information on fire tests conducted on mass timber, an overview of the types of damage that can be expected following a fire event, and rehabilitation methods for wood construction. While no new fire testing or repair methodologies were developed in conjunction with the report, it provides a valuable consolidation of information on these topics.

Specific to fire damage repair, it notes the following:

> *Localized charred wood can be removed with sanding, scraping, or abrasive blasting. Any deeper section can be removed with a chisel or curved blade. After all evidence of char has been removed, affected wood surfaces should be sealed to prevent residual odors.*
>
> *Treated or sealed wood surfaces exposed to smoke should be cleaned to remove any soot residue. Unfinished wood may be more prone to staining from soot deposition and absorption of smoke odors. Unfinished surfaces may require sanding and sealing to prevent residual odors, which can be carcinogenic. Appropriate sealers or treatments should be used. Restored structural members should not have any fire residues remaining before interior finishes are applied.*
>
> *Fire damaged connections require detailed inspection, in particular where connections are in contact with wood because metal parts can conduct heat into wood. The degree of damage to connections depends on the quality of metal and the area of the surface that is exposed to fire. Fire can also result in corrosive effects of connection components from residues that are driven out of wood members in a fire.*

For further investigation into assessment and rehabilitation methods, the report also references useful research from various sources.[13,14,15,16,17]

Appraisal of Existing Structures, Third Edition – The Institute of Structural Engineers, 2010[18]

Section A6.5.3 of this document provides a brief discussion on the repair of fire-damaged timber. Sandblasting and using a sanding plane to remove char are noted as viable options. The paper also notes the importance of assessing and repairing, as necessary, damage to connections and surrounding timber.

Failure Modes and Reinforcement Techniques for Timber Beams – State of the Art[19]

Section 3.3 of this document briefly covers the repair of fire-damaged timber. It suggests removing damaged portions of the members and repairing them by adding wood prostheses, attached to the remaining, original sections with wooden dowels, rods or plates, and utilizing adhesive or other means to bond the fasteners. It notes that the new sections of wood should be of the same species as the original member or at least compatible in terms of structural properties, and the importance of maintaining a consistent moisture content between the original member and prosthesis. The report also describes a method of repair using steel or fiber-reinforced polymer (FRP) rods or plates. This process involves providing temporary support for the damaged member prior to removing affected areas.

Conclusion

Mass timber's ability to act as an exposed structural material, simultaneously functioning as structure, passive fire protection and architectural exposed finish make it a unique and appealing material. Its ability to experience a fire event while retaining its structural integrity also provides designers with a safe, resilient and sustainable structural choice.

As with all materials used in construction, mass timber elements may require repair or replacement after a fire, and the level of damage must be evaluated to determine the appropriate approach. With fire-affected mass timber, the main objectives are to understand the extent of char and heat-affected zones so they can be removed, since structural degradation has occurred. The studies summarized in this document form a base of knowledge that building owners, insurers, and contractors can use to evaluate projects today. As more mass timber buildings are completed, and repair options continue to expand, the data points available to assess mass timber projects will also increase.

WoodWorks offers a range of resources developed for insurance professionals and others seeking to assess mass timber projects, as well as free project support. For more information, visit woodworks.org.

End Notes:

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