WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

ANALYSIS OF CARBONIZED SPEED AND RESIDUAL SECTION OF STEEL-TIMBER CONNECTION

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ABSTRACT: The demand for steel-timber hybrid structures is increasing, particularly in mid-rise and high-rise buildings. In these hybrid systems, connection hardware plays a crucial role; however, its high thermal conductivity can create vulnerabilities at the joints under fire conditions. To address this issue, this study evaluates the thermal distribution of connection hardware with fire-resistant coatings using finite element analysis (FEA). Based on previous studies, five analytical models were developed, incorporating key variables such as the presence of connection hardware, the application of fire-resistant coating, and coating thickness, all subjected to a 3-hour fire exposure scenario. The analysis results indicate that connection hardware accelerates the formation of a char layer at steel-timber joints. However, fire-resistant coatings were found to significantly reduce the char rate and thickness of timber, thereby enhancing fire resistance performance. Notably, as coating thickness increased, the char layer formation within the timber was delayed, leading to a greater residual cross-sectional area. In specimens with a 15 mm fire-resistant coating, the steel temperature remained below its critical threshold throughout the 3-hour fire exposure, demonstrating the feasibility of achieving 3-hour fire resistance performance. Furthermore, by analyzing the char thickness per unit time through differential charring rates, this study suggests that a more accurate fire resistance design can be achieved compared to traditional methods.

KEYWORDS: Joint-Hardware, Steel Timber Connection, Finite Element Method Model, Residual Section, Charring Depth

1 – INTRODUCTION

In response to global climate change, significant efforts are underway to achieve carbon neutrality. Within the construction sector, timber is being re-evaluated as a sustainable structural material due to its ability to reduce carbon emissions. Many countries, including those in Europe, the United States, and Japan, are actively promoting timber-based construction. However, the structural limitations of timber, particularly its strength and stiffness constraints for mid- and high-rise buildings, have led to the increasing adoption of hybrid structural systems. These systems integrate timber with concrete and steel to enhance overall structural performance. This study focuses on assessing the fire resistance performance of mid- and high-rise steel-timber hybrid buildings. To gain a deeper understanding of the fire behavior of steel-timber joints, this study reviews previous research on heat transfer characteristics and fire resistance performance of such connections.

Zhiyuan Liu (2023) conducted heating experiments and temperature distribution analyses on horizontal beams with H-shaped steel embedded within glued-laminated timber (GLT), as shown in Fig. 1(a). The H-shaped steel section was anchored using long bolts placed at 300 mm intervals along the length of the GLT beam. Although the connection hardware was embedded within the timber, the study revealed that heat transfer effects from the hardware intensified over time as the exposure duration to high temperatures increased.

Paul Horne (2023) carried out thermodynamic experiments on column-beam joints with prestressed bolts embedded within the beam, as illustrated in Fig. 1(b). In these experiments, one side of the column was subjected to direct heating, while a load was applied to the beam's end. The findings indicated that the timber reached 300°C within 20 minutes, leading to rapid char layer formation. Temperature measurements using thermocouples positioned near the tension bolts revealed higher temperatures compared to bolt-free regions. Additionally, prolonged steel exposure to elevated temperatures resulted in a significant reduction in yield strength. The study emphasized that the presence of connection hardware plays a critical role in determining the load-bearing capacity of timber joints under fire conditions, highlighting its importance in fire resistance design.

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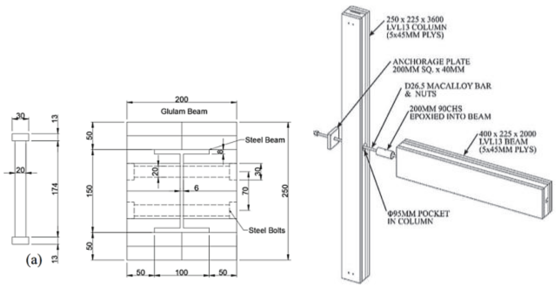
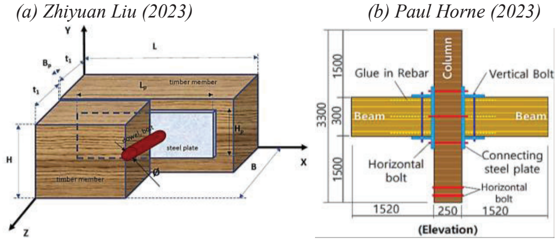
https://doi.org/10.52202/080513-0101



(a) Zhiyuan Liu (2023) (b) Paul Horne (2023)



(c) Abdoulaye Samaké (2014) (d) Park, G.S (2022)

Fig 1. Specific details of Connection (unit: mm)

Abdoulaye Samaké (2014) investigated temperature distribution in joints where timber and steel plates were connected using bolts, with heat applied to all four sides, as depicted in Fig. 1(c). The study compared surface temperatures of exposed timber with temperature variations around the bolts. The results showed that the temperature near the steel connectors was approximately 20°C higher than the surrounding timber, indicating that the high thermal conductivity of steel significantly extends the thermal degradation zone within the timber structure.

Park G.S (2022) proposed a timber moment joint configuration, which was originally evaluated for seismic performance and demonstrated a rotation capacity of 0.03 rad. The joint design, shown in Fig. 1(d), incorporates end plates and through bolts to connect the column and beam. While the original study did not focus on fire resistance, its findings on moment joint details and structural behavior were reinterpreted in the context of fire performance analysis. A finite element method (FEM) model was developed based on these joint details, simulating fire exposure on all four sides for 180 minutes. The FEM model was used to evaluate char thickness, charring rate, and residual cross-sectional area, aiming to assess the adequacy of cross-sectional dimensions and the required thickness of fire-resistant coating for enhanced fire protection.

2. REVIEW OF FIRE RESISTANCE WITH FEM

2.1 Dependability evaluation

Prior to the main analysis, a finite element simulation was conducted to verify the reliability of the thermal distribution results for steel-timber joints by replicating the conditions of Abdoulaye Samaké's (2014) experiment. The simulation was performed using Abaqus CAE (2018) and was based on a Timber-Steel-Timber (TST) joint configuration, as illustrated in Fig. 1(c). The specimen consisted of B20 bolts connecting the timber and steel components. The simulation replicated a high-temperature exposure scenario where the specimen's surface was subjected to fire for 40 minutes, following the ISO 834 standard heating curve. However, in the original experiment, a gas oven was used instead of direct flame exposure, and the thermal properties of the materials were not explicitly specified. To address this limitation, material property values from Eurocode were applied in the simulation. The analysis results, presented in Fig.2 indicated a higher overall temperature distribution compared to the experimental data. Nevertheless, the general thermal behavior and temperature distribution trends remained consistent, with discrepancies limited to less than 10%. This agreement validates the accuracy and reliability of the finite element analysis (FEA) model for evaluating the fire resistance performance of steel-timber joints.

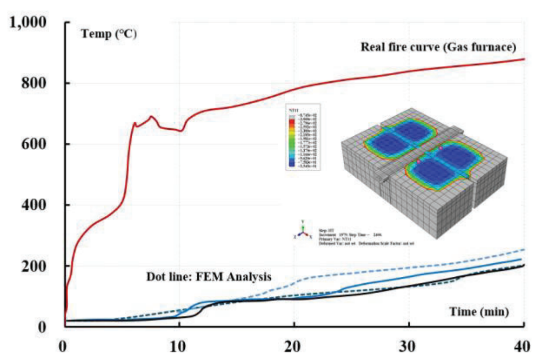


Fig 2. Steel-timber Structure heat distribution [Ref 8]

2.2 Analysis Plan and Boundary Condition

Five finite element analysis (FEA) models were developed to evaluate the impact of connection hardware and fireproof coating thickness on the fire resistance performance of steel-timber joints. In these models, fireproof coating (sprayed material) was applied exclusively to the connection hardware. The list of analysis models is presented in Table 1. The fundamental concept of the steel-timber moment connection model was derived from previous studies. As illustrated in Fig. 3, the connection consists of cross-laminated timber (CLT) columns and beams, which are secured using steel plates and long bolts within the panel zone. The steel plates remain exposed, whereas the bolts are recessed. The connection hardware specifications include M20 (F10T) long bolts and flange steel plates with a thickness of 20

https://doi.org/10.52202/080513-0101

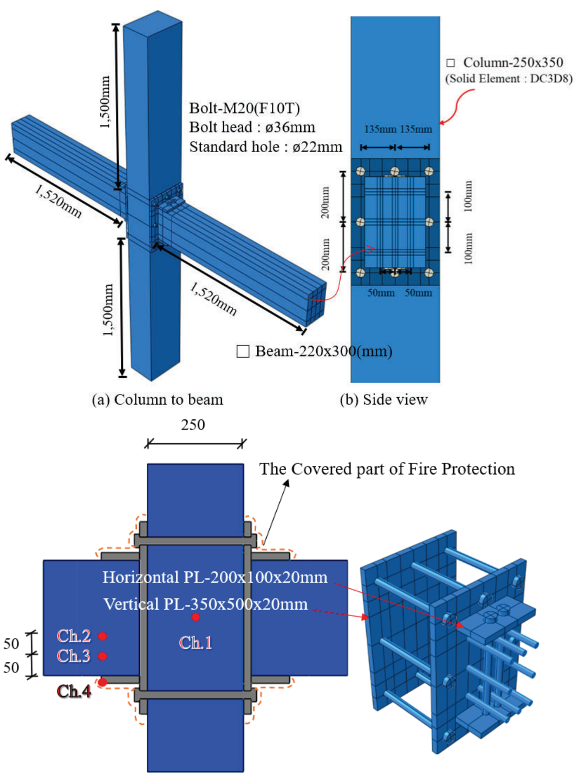
mm. The structural laminated timber used in the model has a strength grade of 10S-30B and is composed of larch. The primary objective of this analysis is to quantitatively assess the carbonization (char) thickness, charring rate, and residual cross-sectional area of the timber components. Temperature measurements were taken at four key locations within the cross-section, as depicted in Fig. 3(c): Ch1. At the center of the column,

- Ch2. 100 mm inward from the beam surface,
- Ch3. 50 mm inward from the beam surface, and
- Ch4. At the interface where the connection hardware contacts the wood

For ALT 1, which represents a model without connection hardware, temperature measurements were taken at the beam surface (0 mm). The analysis was conducted using a solid element approach, with the DC2D4 element type, which is commonly used for linear heat transfer analysis.

Table 1. FEM Model list

FEM Model ID	Type	Spray thickness	Size and Material
ALT 1	Timber (ALL)	-	1) Column : □-250x350mm 2) Beam : □-200x300mm 3) Steel : Fy 355MPa 3) Bolt : M20 (F10T)
ALT 2	Timber + Hardware	0mm	
ALT 3	Timber + Hardware + Fire Protection	5mm	
ALT 4		10mm	
ALT 5		15mm	



(a) Column to beam (b) Side view

(c) Temperature measurement location (d) Joint-Hardware

Fig. 3 FEM Model Concept and detail

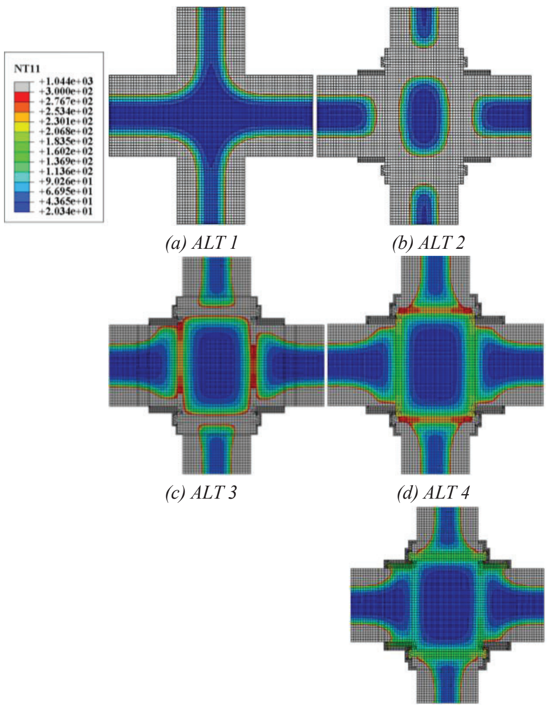
The material properties for steel and wood, including thermal conductivity, specific heat, and density, were applied in accordance with Eurocode 5[3]. The thermal properties of the fireproof spray coating were referenced from Choi (2020). Thermal properties of steel, wood, and the fireproof coating used in the analysis. Since moisture content is challenging to model in finite element analysis (FEA), the bulk density of larch was assumed to be approximately 490 kg/m³ and incorporated into the wood material properties. The fire temperature curve was applied using the ISO 834 standard time-temperature relationship, simulating heat exposure on all four sides [4]. The initial room temperature was set to 20°C using the Predefined Field function in the Load module. These parameters were used to ensure accurate thermal modeling of the steel-timber hybrid joints under fire exposure conditions.

- The following thermal boundary conditions were applied in the analysis:
- Convection heat transfer coefficient (h_a): 25 W/(m²·K)
- Emissivity (ε): 0.8
- Absolute temperature reference: -273.15 K
- Stefan-Boltzmann constant (σ): 5.68×10^{-8} W/(m²·K⁴)

3 – ANALYSIS AND DISCUSSION

3.1 CROSS-SECTIONAL TEMPERATURE DISTRIBUTION

The temperature distribution within the cross-section is summarized in Fig. 4. Regions exceeding 300°C are represented in gray. The charring behavior of the wood varied depending on the presence of connection hardware (ALT1 vs. ALT2). In ALT1, where no connection hardware was present, the charring layers developed uniformly along the beam's length, forming parallel layers in all exposed cross-sections. In contrast, in ALT2, where connection hardware was embedded, charring initiated along the penetrated hardware within the cross-section. As the fire exposure progressed, the internal charring layers extended and eventually merged with the beam’s charring layers. For ALT3–ALT5, which incorporated fire-resistant spray coatings, the overall temperature distribution was significantly lower compared to uncoated specimens. Unlike in ALT2, where charring propagated extensively around the connection hardware, the coated specimens (ALT3–ALT5) exhibited a more localized charring pattern, with narrower char layers surrounding the hardware. Additionally, the charring layer near the steel plate developed at a slower rate due to the insulating effect of the fire-resistant coating. The thermal distribution patterns of ALT3–ALT5 indicated that increasing the thickness of the fire-resistant coating effectively delayed the formation of the wood charring layer. Among the five tested specimens, only ALT5 (with 15 mm of fire-resistant coating) successfully maintained the steel temperature below 649°C for the entire 180-minute fire exposure duration, demonstrating its effectiveness in achieving the required fire resistance performance.



(a) ALT 1 *(b) ALT 2*

(c) ALT 3 *(d) ALT 4*

(e) ALT 5

Fig 4. Cross-sectional temperature distribution (At the 120min)

Fig.5 presents the temperature distribution profiles extracted from the cross-sections of each analytical model. The analysis revealed a common trend: the temperature within the cross-section initially increased gradually up to approximately 100°C, followed by a temporary plateau, and then a sharp increase. This behavior reflects the thermal response of timber, where pyrolysis initiates as the moisture content within the wood evaporates at around 100°C. To evaluate the charring layer formation, the time required to reach 300°C (the threshold temperature for charring) was analyzed at a cross-sectional depth of 50 mm. The observed charring times for each model were 78, 81, 113, 127, and 147 minutes, respectively. Contrary to expectations, ALT2 exhibited a slightly delayed charring onset compared to ALT1 (by approximately 3 minutes). This delay can be attributed to the presence of connection hardware, which insulated the underlying wood from direct fire exposure, causing the charring layer to form primarily through heat conduction from the embedded hardware rather than direct combustion. At a depth of 100 mm, a significant difference in temperature progression was observed:

- ALT1 did not reach 300°C, even after 3 hours of fire exposure, indicating relatively slow heat penetration.
- ALT2, due to the thermal conductivity of the vertical flange steel plate, exhibited a more accelerated charring process, with temperatures reaching approximately 400°C.
- ALT3, ALT4, and ALT5, which incorporated fire-resistant coatings, maintained temperatures below 100°C throughout the test, confirming that the fire-resistant coating effectively prevented heat transfer from the connection hardware to the interior of the timber.

These findings highlight the critical role of connection hardware in influencing internal charring behavior, as well as the effectiveness of fire-resistant coatings in minimizing heat conduction and delaying charring layer formation.

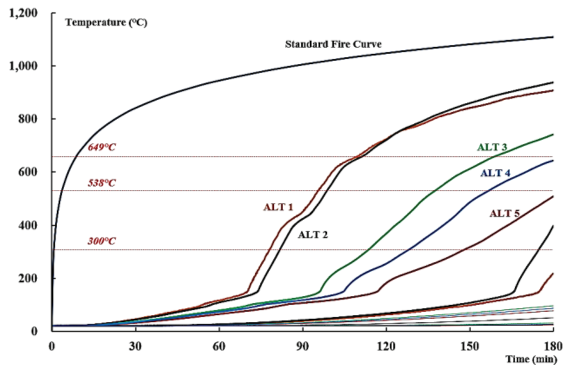


Fig 5. Time-Temperature relationship

3.2 CHARRING THICKNESS

The cross-sectional size of timber is the most critical factor influencing its fire resistance performance. As illustrated in Fig. 6(b), only the residual cross-section, excluding the charred layer, contributes to the structural load-bearing capacity. Therefore, char thickness is a key parameter in fire-resistant design. While increasing the cross-sectional size can enhance fire resistance, adopting an overly conservative design approach is often impractical for fabrication and construction and can lead to significant inefficiencies in material usage and cost. Consequently, a more effective strategy is to delay the formation of the charred layer through an optimized cross-sectional design and fire-resistant coating application. Fig. 6(a) presents the relationship between char thickness and fire exposure duration. The analysis demonstrates a proportional trend, where char depth increases over time, with the gap between specimens widening as exposure duration increases. When comparing the char thickness of models with and without connection hardware, the results indicate similar char depths in the early stages. However,

https://doi.org/10.52202/080513-0101

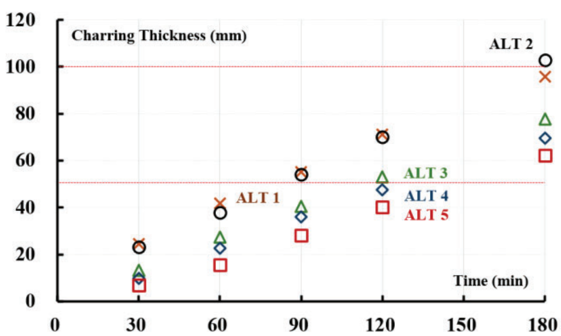
at 180 minutes of fire exposure, a distinct difference emerges:

(1) ALT2 (with uncoated connection hardware) exhibited the greatest char thickness, reaching 102.6 mm, the highest among all specimens.

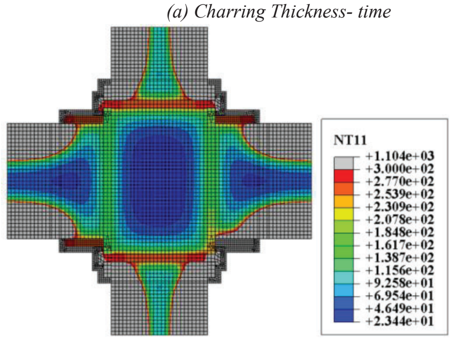
(2) In contrast, for fire-resistant coated specimens (ALT3–ALT5), the char thickness progressively decreased as the coating thickness increased, measuring:

- 77 mm for ALT3 (5 mm coating),
- 69 mm for ALT4 (10 mm coating), and
- 62 mm for ALT5 (15 mm coating).

These findings highlight the significant influence of fire-resistant coatings in reducing char depth and enhancing fire resistance performance, particularly over longer fire exposure durations.



(a) Charring Thickness- time

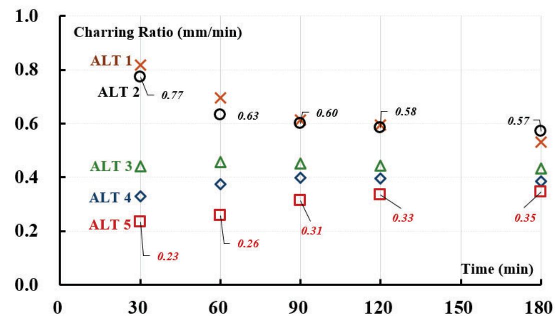


(b) Temperature distribution (ALT 5, 180min.)

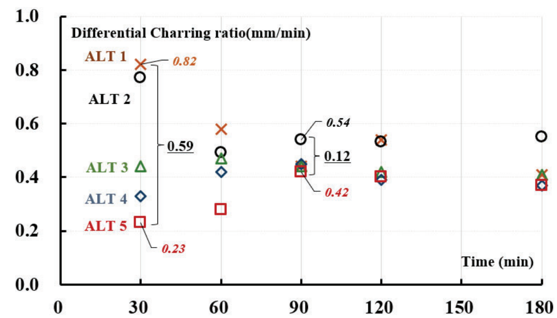
Fig 6. Behavior of specimen Charring depth

3.3 Differential charring rate(DV)

The traditional method for calculating charring rate has a notable limitation in that it does not account for variations in charring thickness over time. For a more precise fire resistance design of timber structures, it is essential to consider the progression of charring thickness at different time intervals throughout the fire exposure period. To address this issue, the differential charring rate was introduced. This rate is determined by dividing the measured charring thickness per unit time by the corresponding time interval. The computed values are presented in Fig. 7. The differential charring rate was evaluated at 30-minute and 60-minute intervals to capture the temporal variations in charring behavior. In the first 30 minutes, the differential charring rate matched the initial charring rate, as the total charring thickness at each interval was simply divided by the fire duration. This value also represented the average charring rate over the full 180-minute fire exposure period. These results provide a more detailed understanding of how the charring process evolves over time, which is crucial for optimizing fire-resistant design strategies in steel-timber hybrid structures.



(a) Normal Charring ratio



(b) Differential Charring ratio

Fig 7. Comparison of high temperature exposure time intervals

With the exception of the first 30 minutes of fire exposure, all specimens exhibited charring rates below 0.65 mm/min. For ALT1 and ALT2, the charring rate peaked at 30 minutes, coinciding with the onset of pyrolysis and initial charring layer formation. The measured charring rates ranged between 0.41–0.82 mm/min for ALT1 and 0.49–0.77 mm/min for ALT2. As the fire exposure progressed, the charring rates declined significantly, reaching lower values by the 60-minute mark. According to the traditional charring rate calculation method, ALT2 exhibited a slightly lower average charring rate than ALT1, despite the presence of connection hardware, which was expected to accelerate charring. However, when analyzed using the differential charring rate method, which accounts for charring thickness per unit time, ALT2 showed a higher differential charring rate than ALT1 starting from the 90-minute mark. This increase in differential charring rate can be attributed to the formation of internal charring layer compartments within the timber section, caused by the

embedded connection hardware. These compartments likely altered the heat transfer dynamics, leading to a more localized charring process within the structure.
For the fire-resistant coated specimens, ALT3 exhibited an increasing differential charring rate up to 60 minutes, after which it gradually decreased. In contrast, ALT4 and ALT5 displayed a continued increase in differential charring rates up to 90 minutes, followed by a decrease to within 0.1 mm/min, after which they stabilized. Overall, the differential charring rates of the fire-resistant coated specimens were higher than their respective average charring rates. This suggests that the traditional charring rate calculation method provides a more conservative estimate of char layer development, particularly in uncoated specimens, as it does not fully account for time-dependent variations in charring behavior.

The differential charring rate serves as a key indicator for assessing charring progression over time and plays a crucial role in the fire resistance design of timber structures. By analyzing differential charring rates in relation to connection types, member locations within a structural frame, and fire-exposed surfaces, it is possible to identify structural members that are more or less susceptible to fire damage. This information can support rational decision-making regarding the optimal sizing of timber cross-sections and the application of fire-resistant coatings to enhance overall fire performance. Future research should further investigate differential charring rates with a focus on various fire exposure conditions, enabling a more precise evaluation of fire resistance in timber structures.

3.4 RESIDUAL CROSS SECTION RATIO

The residual cross-section is defined as the remaining uncharred portion of the total cross-sectional area after fire exposure. This value serves as a key indicator of the load-bearing capacity of timber in fire conditions relative to ambient temperature conditions. The residual cross-sectional ratio can vary depending on the size of the cross-section and the fire-exposed surfaces. However, when expressed as a proportion of the total cross-sectional area, it provides meaningful insights into the fire performance of timber structures. As illustrated in Fig. 8, a comparison of residual cross-sections after 3 hours of fire exposure revealed significant differences among the tested specimens:

- ALT1 (without connection hardware) retained 40% of its original cross-section.
- ALT2 (with uncoated connection hardware) exhibited a significantly reduced residual cross-section of only 19%, highlighting the accelerated charring effect caused by the embedded steel components.
- ALT4 and ALT5, which were coated with at least 10 mm of fire-resistant material, retained over 50% of their cross-sections, with ALT5 achieving a particularly high ratio of 67%.

The results confirm that increasing the thickness of the fire-resistant coating helps mitigate the reduction in residual cross-section over prolonged fire exposure. Specifically, based on the residual cross-section of ALT3 after 3 hours, the study found that:

- Doubling the coating thickness (from 5 mm to 10 mm) increased the residual cross-section by 11%.
- Tripling the coating thickness (from 5 mm to 15 mm) resulted in a 24% increase in the residual cross-sectional ratio.

These findings suggest that thicker fire-resistant coatings significantly improve the fire resistance performance of steel-timber joints. Since connection hardware is positioned at the column-beam interface (panel zone), even slight temperature reductions can lead to substantial improvements in fire resistance. Additionally, in ALT5 (with a 15 mm fire-resistant coating), the connection hardware remained below the steel's critical temperature limit of 300°C, and the charring layer inside the timber did not develop compartmentalized patterns, further confirming its fire protection effectiveness.

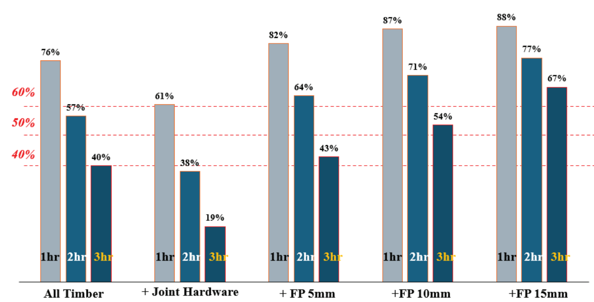


Fig 8. Residual section ratio per time

4 – CONCLUSION

This study evaluated the 3-hour fire resistance performance of steel-timber joints with connection hardware by conducting a thermal distribution analysis, considering variables such as coating thickness and the presence of connection hardware. The study compared the temperature distribution, charring layers, charring rates, and residual cross-sectional ratios of timber specimens with and without connection hardware, as well as those with fire-resistant coatings. The key findings are as follows:

(1) Connection hardware used in timber joints primarily initiates charring within the wood and acts as a key factor in compartmentalizing the charring layer. However, it was observed that it only accelerates the formation of the charring layer within the cross-section and does not directly affect the temperature rise of the wood itself.

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(2) It was confirmed that fire-resistant coatings effectively suppress the temperature rise within the cross-section. The charring rate of specimens with fire-resistant coated connection hardware averaged 0.30–0.44 mm/min, which is about 42% lower than that of uncoated specimens.

(3) Analysis of the differential charring rates by unit time revealed that uncoated specimens, while initially disadvantageous in charring rate formation, showed reduced charring thickness per unit time due to charring layer formation. For coated specimens, regardless of the coating amount, the charring rate decreased and stabilized after 90 minutes. Therefore, it was observed that there is no need to continuously increase the coating thickness in proportion to the fire duration.

(4) Based on charring thickness, ALT2 had the lowest remaining cross-sectional ratio at 19%. The remaining cross-section was found to be directly proportional to the coating thickness. For ALT3, it was observed that doubling the coating amount increased the remaining cross-section by 11%, and tripling it increased the remaining cross-section by 24%.

(5) Out of the five specimens tested, only ALT5 with 15 mm fire-resistant coating did not exceed the steel temperature limit of 658°C, and the internal charring layer of the wood was not preemptively compartmentalized. With continuous cross-sectional distribution and the low thermal conductivity of the coated connection hardware, it is concluded that ALT5 can achieve 3 hours of fire resistance performance.

Acknowledgment

This study was carried out with the support of ´R&D Program for Forest Science Technology (Project No. "RS-2004-00400729)´ provided by Korea Forest Service(Korea Forestry Promotion Institute).

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