WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

A Study on Charring Properties of Glued Laminated Timber Beams Using Domestic Larch

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ABSTRACT: In Korea building laws and regulations require building structure members of a certain size or larger to have a fire resistant structures. Internationally, timber structure fire resistance measures apply the charring rate and charring depth of wood exposed to high temperatures to fire resistance design and are considered to have secured fire resistance performance through cross-sectional design with a charring depth. In Korea, the criteria for recognizing the fire resistance structure of wood members are charring depth per hour, and the member design should be applied by applying the charring depth for wood structure buildings. In this study, fire resistance performance tests are performed on structural beams made of domestic larch, and charring properties are analyzed and the results. To this end, Load bearing fire test was conducted on the structural member(GLT). The results of the fire resistance test considered the are charring depth according to the fire resistance time, the charring depth change according to the charring rate and the load ratio change.

KEYWORDS: Fire resistance performance, Korea larch, Glued laminated timber, Charring properties

1 – INTRODUCTION

With carbon emissions accelerating global warming and climate change, there are global efforts to develop strategies for carebon reduction. Wood, recognized for its excellent carbon storage capacity, is considered a sustainable and environmentally friendly material. However, the carbon storage capacity of wood declines as trees reach a certain age. Therefore, timely harvesting and planting of sapling are crucial for effective carbon sequestration. In korea, the ability of trees to absorb carbon begins to devline after they reach 30 years of age[1]. Currently, approximately two-thirds of the timber in Korea consists of older trees that have diminished carbon absorption capacity[2]. To reduce carbon emissions and promote the circulation of timber resources, there is an urgent need to utilize Korean timber, which has strong carbon storage potential. In the construction sector, wood should be employed in the structural elemets of buildings to facilitate this resource circulation. One cubic meter of timber can absorb 1ton of carbon dioxide and store 250kg of carbon. Additionally, timber is highly competitive as a structural material, offering superior tensile strength, compressive strength, and flexural strength per unit weight compared to steel or concrete. Furthermore, timber provides excellent thermal insulation, with insulating performance that is ten times better than concrete and 500 times better than steel[3].[4]. As a result, an increasing nember of diverse structures are being constructed with timber worldwide, leveraging these advantageous characteristics.

Wood is natural material that can exhibit physical variations even within the same species, influenced by the region or environment during growth. To control these physical properties and ensure quality as a building material, raw wood is processed for structural use, resulting in products known as “engineered wood.” Two major forms of engineered wood are glue-laminated timber and cross-laminated timber. Glued-laminated timber is frequently used in the structural elements od wooden buildings[5]. The primary structural elements of

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https://doi.org/10.52202/080513-0677

buildings must prssess adequate fire resistance to prevent collapse during a fire. Accordingly, Korean construction law mandates fire-resistanct structures in buildings exceeding a certain size, requiring that the structural elements maintain performance even when exposed to high temperatures for a specified duration. Structural elements in wooden building must also be designed to be fire-resistant. Internationally char rate and char depth are key concepts in designing fire-resistant wooden structures, with fire resistance performance demonstrated through sections that display the char layer[6]. In South Korea, the criterion for recognizing the fire resistance of wooden elements is based on char depth over time, and wooden building elements must be designed according to the approved char depth. Since the char layer provides minimal load-bearing support, the char properties of wood are crucial for evaluating fire resistance performance[7].

Wooden buildings utilize glue-laminated timber with various cross-sectional sizes depending on the intended use and required fire resistance performance. The cross-section of structural elements infuluences usable area and zoning.

The purpose of this study was to conduct fire resistance tests on structural glue-laminated timber beams made from Korean larch and analyse the char properties. For this puepose, we fabricated specimen beams with different cross-sectional shapes and areas. Which then underwent load-bearing fire sesistance tests. We analysed the test results, focusing on char depth, char rate, and changes in char thickness vased on the aspect ratio of the beams.

2 – BACKGROUND

In South Korea, the criterion for recognizing the fire resistance of wooden elements is the char depth over time, and the recognized char depth must be applied to the design of elements in wooden structures. For the production of glue-laminated timber, the South Korea market currently uses mostly North American larch wood, with, which reduces domestic carbon emissions, improves the circulation of wood resources, and has excellent carbon storage capacity, instead of foreign wood, which is not considered in the calculation of domestic carbon emissions. Thus, there is a clear need to promote the use of domestic wood. This study aimed to carry out fire tests on glue-laminated beams made from domestic larch, and to analyse and report the charring properies. Specifically, we carried out boyh load-bearing and non-bearing fire tests on glued laminated timber beams. For the results of fire tests, we considered char fepth over time, char rate, and changes in charnges in charge depth at different load conditions.

3 – Wood charring and fire resistance tests

3.1 Pyrolysis and charring

Wood undergoes pyrolysis within a specific temperature range. As wood is gradually heated from room temperature, the water content begins to evaporate, primarily being driven off around 100°C. Above this temperature, wood breaks down at the molecular level. Between 100°C and 200°C, carbon dioxide and carbon monoxide are released alongside water vapor in the form of steam. Pyrolysis of wood starts at approximately 120°C, and at temperatures exceeding 200°C, charring occurs rapidly due to dehydration.

When heated, pyrolysis results in the formation of a char layer and the production of volatile gases. At temperatures below 300°C, the char layer forms as a byproduct of pyrolysis. However, at temperatures above 300°C, the generation of volatile gases increas-es significantly, becoming the primary product of pyrolysis. After the release of volatile gases, the remaining char layer thickens over time, which tends to reduce the char rate[8].

The boundary between the char layer and the residual section is distinctly defined, with the temperature at this boundary typically around 300°C[9]. The residual section re-fers to the structural cross-section that retains the structural performance of wooden ele-ments during a fire. Figure 1 illustrates a cross-section of a glue-laminated timber beam after exposure to high temperatures.

Figure 1 A charring layer of timber exposed to fire resistance test

https://doi.org/10.52202/080513-0677

3.2 Fire resistance design for wooden structures

The formation of a char layer, as described above, protects the residual cross-section, allowing the element to maintain its performance even as the fire progresses. Structural design specifications are based on the residual section, and the final cross-section of the element is calculated by considering the char depth required for the specified fire-resistance duration.

South Korea has a system for accrediting the fire resistance of structural elements in buildings. For wooden elements, the char depth verified through fire resistance tests is used to ensure adequate fire resistance performance. In contrast, other countries often use the char depth of the wood, as calculated from the char rate, in fire resistance design.

When wood is exposed to fire, if the temperature exceeds a certain level, burning oc-curs. When the breadth (b) × length (d) of a section of wood is exposed to fire, and reduced to a residual section of bf × df , the char depth of the exposed section can be calculated us-ing the equations below.

$$c = \beta t \tag{1}$$

c = char depth (㎜), β = char rate (㎜/min), t = time (min)

As shown in Figure 2, the residual section after the formation of the char layer can be obtained as follows:

bf (breadth of the residual section) = b-2c

df (length of the residual section) = d-c (heating applied to 3 faces)

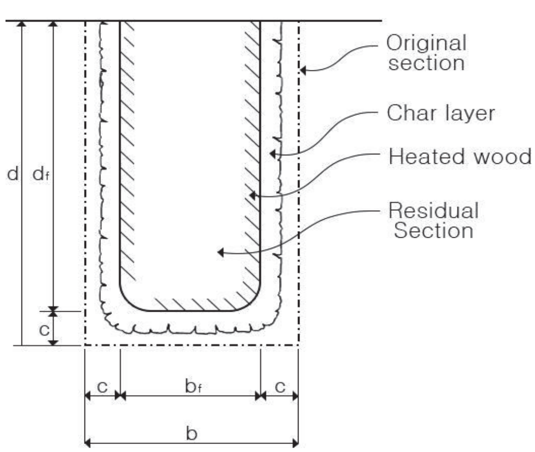


Figure 2 Fire resistance design concepts for timber members

The design char rates recommended in the Eurocodes [6] (European technical stand-ards that offer a harmonized approach to the structural design of buildings) are presented in Table 1. The char depth specified in the Eurocode standard is derived from the rela-tionship between the char rate β, char depth, and time, as shown in the equations above. Since corner areas experience approximately 10% more charring compared to the rest of the section, both a one-dimensional char rate (β0) and a notional char rate (βn) for corners are provided.boratory-based or other research & development projects, this section will describe the specimens, and the type of tests undertaken. For abstracts addressing an engineering.

Table 1 Design charring rates β_0 and β_n of timber (Eurocode 5)

Meterial	Minium density (kg/m^3)	Char rate	
		β_0 (㎜/min)	β_n (㎜/min)
Glue-laminated softwood timber	290	0.65	0.70
Solid or glue-laminated hardwood timber	450	0.50	0.55

The Wood Handbook published by the American Forest and Paper Association [10] proposes both linear and non-linear models for char depth, while the American Wood Council's National Design Specification (NDS) for Wood Construction employs the non-linear model. In this context, the species-specific char rates outlined in the ASTM Standard Test Methods for Fire Tests of Building Construction and Materials (E 119) are substituted into the equations below to calculate char depth for use in fire resistance de-sign.

$$t = mxc^{1.23} \tag{2}$$

t = time (min), m = char rate (㎜/min), xc = char depth (㎜)

4 – Evaluation of fire resistance performance and results

4.1 Summary of test specimens

To investigate the char properties in relation to the aspect ratio and cross-sectional area of glue-laminated timber, we prepared test specimens from Korean larch. Fire resistance tests were conducted to examine the influence of aspect ratio on char properties by preparing specimens with the same cross-sectional area but differing widths and heights. The density of the test specimens ranged from 290 to 450 kg/m³.

As major structural elements of buildings, beams are typically load-bearing, necessi-tating relevant load-bearing fire tests. The observed char properties, including char depth behavior and char rate, were analyzed. Loading was calculated based on the residual sec-tion, using the design char rate suggested in Eurocode 5. A 60-min fire test was conducted with a test load corresponding to the calculated residual section (load ratio 1.0).

To evaluate the adequacy of fire resistance performance, we applied the displacement criteria suggested for load-bearing performance in the Korean industrial standard KS F 2257-1 (Methods of fire resistance tests for elements of building construction—general re-quirements)[11]. Table 2 characterizes the glue-laminated timber beam specimens of Korean larch prepared for this experiment.

The moment of inertia of structural glue-laminated timber beams varies with the as-pect ratio. The beams were observed to experience vertical stress, potentially resulting in differing char properties between the upper and lower sections. This study examines the correlation between the beam's char performance and moment of inertia in relation to the cross-sectional area ratio.

Table 2 Summary of fire resistance test specimens (Test time 60min.)

Specimen	Size(W*H)	Test load (kN)	Aspect Ratio (W/H)	Moment of inertia (cm^4)
B-L-1	500*600	80.5	5/6	900,000
B-L-2	200*600	13.1	1/3	360,000
B-L-3	200*500	10.5	2/5	208,333
B-L-4	200*400	7.5	1/2	106,667
B-L-5	400*200	4.7	2/1	26,667

4.2 Test summary

The fire resistance performance tests were conducted in accordance with Korean industrial standards KS F 2257-1 and KS F 2257-6 (Methods of fire resistance tests for elements of building construction—specific requirements for beams)[12]. For the fire temperature curve, we utilized the standard time-temperature curve from ISO 834-1 (Figure 3) and measured the char depth of the specimens as well as their displacement under load.

The testing procedure employed a fire resistance test furnace equipped with a burner using liquefied natural gas as fuel. The furnace had three closed sides. A load was applied at four points on the top of the specimen using a hydraulic loading device positioned at the top of the furnace. The peak load was set at 500 kN, with a peak compression length of 1,000 mm. Figure 4 illustrates the loading device and the configuration of the load-bearing tests.

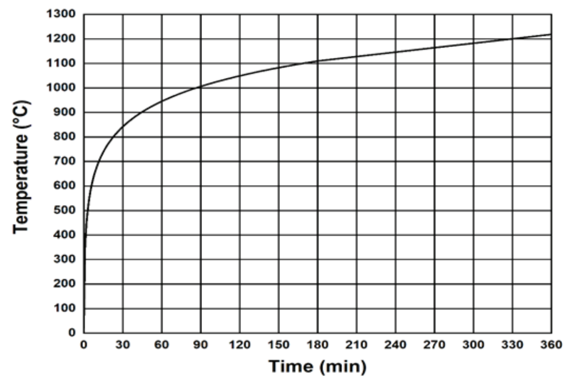


Figure 3 Standard time-temperature curve (ISO 834-1)

Figure 4 Furnace for testing fire resistance of structural wooden beams

4.3 Measuring char depth

Char depth was measured from sections taken at three evenly spaced locations along the length (L) of each specimen. At each section, char depth was measured at four locations, resulting in a total of 12 measurements per specimen. Figure 5 illustrates the locations for sectioning each specimen and for measuring char depth at each section.

4.4 Test results

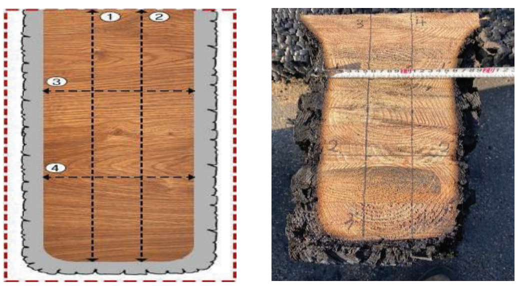
Table 3 presents the fire resistance results for glue-laminated beams made of Korean larch with varying cross-sections. We assessed the performance of the

https://doi.org/10.52202/080513-0677

specimens based on displacement under load, following the guidelines outlined in KS F 2257-1 (Methods of fire resistance test for elements of building construction – general requirements). All five specimens exhibited significantly less displacement than the maximum allowable limit, confirming their compliance with fire resistance standards.

With the exception of B-L-4, which showed considerable carbonization, the char depth for the remaining specimens ranged from 37.2 to 38.3 mm.

(a) Measurement locations after fire resistance test



(b) Charring depth measurement points

Figure 5 Charring depth measurement of specimens

Table 3 Results of fire resistance tests

Specimen	Displacement (mm)	Charring depth (mm)	Charring rate (mm/min)	Aspect ratio (W/H)
B-L-1	1.9	37.3	0.62	5/6
B-L-2	2.2	37.5	0.63	1/3
B-L-3	0.6	38.1	0.64	2/5
B-L-4	2.0	43.2	0.72	1/2
B-L-5	5.1	38.3	0.64	2/1

5 – Discussion of the fire resistance test results

5.1 Change in displacement

All five glue-laminated Korean larch beam specimens underwent a 60-min fire re-sistance test in a furnace. All specimens exhibited very stable displacement behavior, meeting the performance criteria. While it is typical for elements like beams to demon-strate increased displacement with rising load, our test specimens did not show any sig-nificant differences in displacement behavior. Figure 6 illustrates the changes in dis-placement over the test duration.

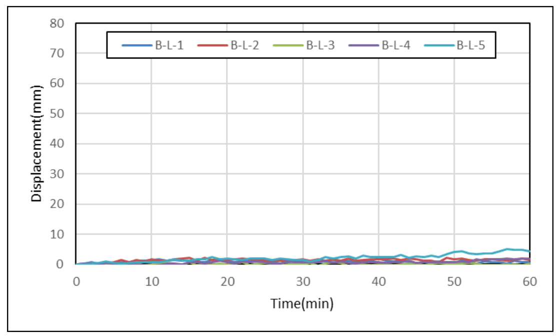


Figure 6 Displacement of glue-laminated beam specimens over time during fire resistance test

The minimal change in displacement observed in the glue-laminated timber beams in our study is likely due to differences in the method of calculating the test loads. Typi-cally, test loads for beam components are calculated relative to the total cross-sectional area of the specimen. However, since glue-laminated timber develops a char layer, the load is assessed based on the residual area after the char layer is removed. This char layer continuously protects the structural section throughout the fire resistance test, resulting in minimal damage to the structural integrity. At load ratios where the test load is less than the external forces considered during design, it seems that the loads were insufficient to significantly impact the specimens' displacement.

5.2 Changes in char depth

We examined the effects of cross-sectional size on char depth across five specimens. By comparing the estimated char depth based on the Eurocode standard (applying a safety factor of 10% of the load) with the measured char depth of the specimens (excluding specimen B-L-4), we found a difference of 3% relative to the one-dimensional char rate ($\beta 0$) and 10% compared to the notional char rate (βn).

In Figure 7, which illustrates the char depth measured at each of the 12 locations for each specimen, we observe variations in char depth measurements between the width and height dimensions due to the heating of the beam elements on three sides. This discrep-ancy likely explains why only specimen B-L-4, which had a shorter height, exhibited more significant charring.

5.2.1 Effects of width on char depth

We compared the char depth between specimens B-L-1 and B-L-2, which were of the same height (H). As shown in Table 3, although these two specimens had different cross-sectional areas due to their varying widths (W), the char depths were comparable.

5.2.2 Effects of height on char depth

We compared the char depths among specimens B-L-2, B-L-3, and B-L-4. As shown in Table 3, the cross-sectional areas varied significantly due to their differing heights (H). While relatively weak, Figure 8 indicates a trend suggesting that char depth develops more rapidly with shorter heights.

5.2.3 Effects of width (W) and height (H) on char depth at constant cross-sectional area

We compared the char depths between specimens B-L-4 and B-L-5. Although these specimens had the same cross-sectional area of 800 cm², they exhibited a 13% difference in char depth. The graph in Figure 9 illustrates the relationship between cross-sectional area and char depth for each of the five specimens. Based on these results, we concluded that, when the cross-sectional area remains constant, greater char depth occurs when the width is shorter than the height. In summary, despite identical cross-sectional areas, the differ-ing moment of inertia values indicate a variation in char properties.

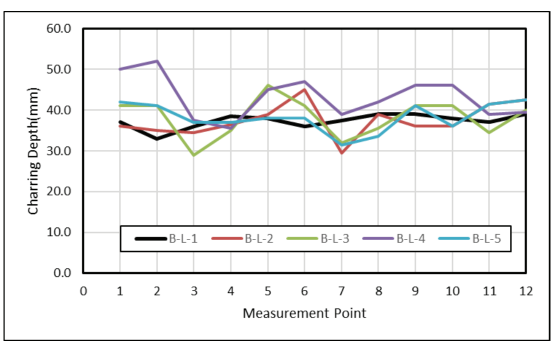


Figure 7 Resullts of charring depth by measurement point

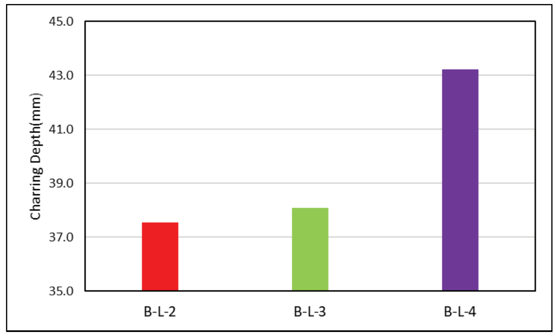


Figure 8 results of charring depth by specimen height (H)

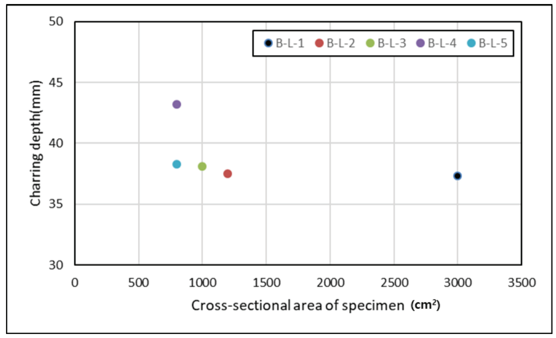


Figure 9 The cross-sectional area of specimens and charring depth

6 – CONCLUSION

We conducted load-bearing fire resistance tests on beams made from glue-laminated Korean larch timber and obtained the following results regarding their char properties.

First, with the exception of specimen B-L-4, all other specimens exhibited a char depth that differed by 3% compared to the one-dimensional char rate ($\beta 0$) and 10% com-pared to the notional char rate (βn) as estimated by the Eurocode standard, applying a safety factor of 10% of the load. We concluded that, for the smaller specimens, the beam's width influenced char properties more significantly than its length.

Second, in glue-laminated timber, the residual cross-section serves as the structural section that withstands external forces. We determined that applying an external force with a 1.0 load ratio on the residual section had minimal impact on displacement.

Third, for smaller specimens, we observed that, at a constant cross-sectional area, charring was more pronounced when the width was less than the height. This phenome-non is attributed to vertical forces acting on the

https://doi.org/10.52202/080513-0677

beams, which cause the char layer in the lower part to dislodge and subsequently be replaced.

Given the increasing use of engineered wood products, glue-laminated timber has garnered attention as a viable construction material. In this study, we analyzed the char properties of load-bearing glue-laminated beams made from Korean larch. We believe our findings can serve as a valuable reference for research and development in fire resistance design standards for wooden structures utilizing Korean timber, particularly when comparing results with char rates and char depths documented in other markets and jurisdictions.

7 – Acknowledgement

This study was conducted with the support of the R&D Program for Forest Science Technology (Project No. “RS-2023-KF002506”) provided by the Korea Forest Service (Korea Forestry Promo-tion Institute).

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