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A Study on the Charring Properties of Glued Laminated Korean Larch Timber Columns

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Abstract: As the carbon storage capacity of timber is recognized, there is growing interest in timber and wooden structures as a solution to various environmental problems. The use of Korean timber with substantial carbon storage capacity is required to reduce Korean carbon emissions and circulate timber resources. In this study, fire tests were conducted to investigate the charring properties of glued laminated timber columns made of Korean larch. The fire tests were conducted under both load-bearing and non-load-bearing conditions. The fire test results showed that the charring depth was affected by the corners of the section and that the load ratio had an insignificant influence on the charring depth when the load ratio was 0.9 or less. This study provides data that can be used to compare the charring properties of laminated wood produced using South Korean larch with the charring properties of foreign standards. This research provides reference data for developing fire-resistant design standards for timber structures made from South Korean timber.

Keywords: charring properties; fire resistance performance; glued laminated timber; Korean larch; timber recycle

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1. Introduction

With carbon emissions accelerating global warming and climate change, there are global efforts to develop strategies for carbon 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 saplings are crucial for effective carbon sequestration. Even within the same species, timber exhibits variation in its physical characteristics based on the local climate and surroundings [1].

Engineered wood refers to wood that was processed in its natural state to control changes in physical properties and ensure the consistent quality of building materials. Engineered wood is presented in various forms, such as cross-laminated and glued laminated wood. Glue-laminated wood is commonly used for the columns and beams comprising the main structural components of wooden buildings [2]. Korean building law requires that the structural elements of buildings above a certain size be fireproof. Fireproofing structures using the main structural elements of the building is intended to prevent the collapse of the structure in the event of a fire. A structure is considered fireproof if it can continue to function after being exposed to high temperatures for a predetermined period of time; the structural elements in wooden construction must also be fireproof. According to a previous study [3], fires in wooden buildings typically start burning quickly and peak faster than other structures, leading to the perception that they are vulnerable to fire. However, wood is often used in the structural elements of buildings because its thermal conductivity is approximately 350 times lower than that of iron, and wood is more suitable for re-use in structures after exposure to fire than steel or concrete. As the scale of wooden construction and the demand for taller buildings increases, the use of glued laminated timber and other forms of engineered wood is expected to gradually increase. Internationally, the approach to fireproofing wooden structures considers factors such as the charring rate and charring depth of wood exposed to relatively high temperatures, and cross-sectional structures that have a charring layer are considered evidence of fire resistance performance.

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. To produce glued laminated timber, the South Korean market currently uses mostly North American larch wood, with some European spruce. Owing to the unique characteristics of Korean forests, it is only possible to produce structural timber using Korean larch; therefore, it was used in this study.

Recently, there has been a demand for structural elements made of Korean wood, which reduces Korea's 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 Korea's carbon emissions. Therefore, there is a clear need to promote the use of Korean wood.

Glued laminated wood is manufactured by laminating lumber with a proven mechanical strength grade. However, even engineered wood has limited ability to maintain consistent quality, including strength, at high temperatures. As a result, even hardwood can exhibit differences in charring properties when exposed to high temperatures in a fire, depending on the growing environment. This lack of consistency means that even the same species of larch can have differences in charring properties depending on whether it originates from North America or South Korea. Within the same species, differences in wood density and chemical composition can lead to variations in carbonization performance [4,5]. Previous studies on the fire resistance and charring properties of glued laminates mostly used wood from overseas trees, making it difficult to find previous cases where glue laminates from South Korean trees were used. Manufacturers of glued laminated timber primarily use foreign trees owing to various factors, including the economic and production characteristics of the raw wood.

Korean lumber, which has a very low supply volume and is more expensive than foreign lumber, is seldom used to produce glued laminated timber in South Korea's glued lamination industry. Consequently, glued laminated timber from local trees is disregarded in the Korean wood-building industry. One reason for this disregard is that, although wood from the same tree species can exhibit differences in charring properties depending on the weather or climate of the region in which it grows, research on the charring properties of Korean trees is significantly lacking.

According to a previous study [6], the char layer formed when the internal temperature of wood rises >300 °C and remains unstable; therefore, char properties are essential for evaluating fire resistance. The carbon layer is created through a pyrolysis process when wood is exposed to high temperatures and acts as fire-proof insulation, preventing the transfer of heat from outside to inside the wood. In turn, this prevention of heat transfer reduces the production of volatile gases owing to pyrolysis and ensures resistance to high temperatures in the event of a fire.

The aim of this study was to conduct fire tests on glued laminated columns made from Korean larch and analyze and report the charring properties. Specifically, both load-bearing and non-load-bearing fire tests were conducted on glued laminated timber columns. The fire tests considered the char depth over time, char rate, and changes in charge depth at different load conditions. This study provides data that can be used to compare the charring properties of laminated wood from South Korean larch with the charring properties, including charring rate, of foreign standards, which is useful reference data for developing fire-resistant design standards for timber structures made from South Korean timber.

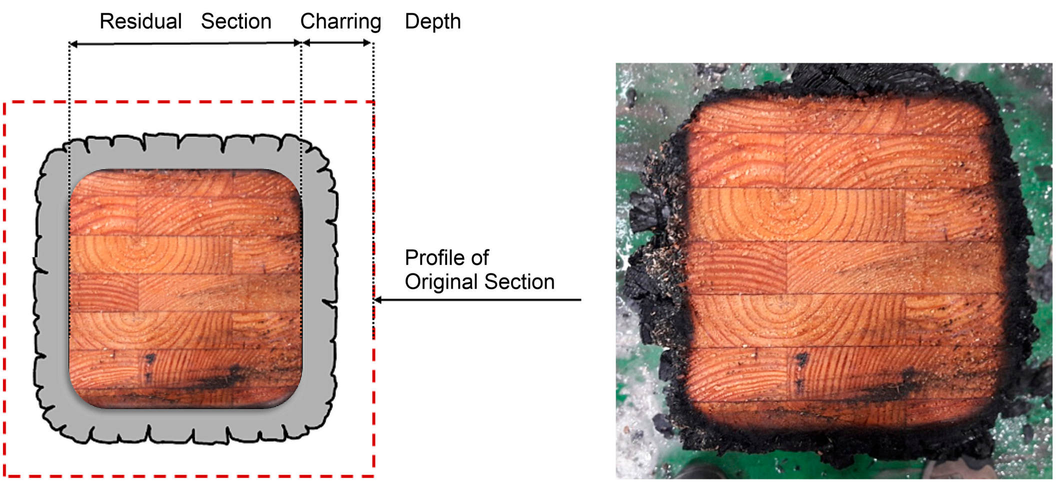
2. Wood Charring and Fire-Resistant Design Theory

2.1. Pyrolysis and Charring

According to a study conducted by Dietenberger et al. [7], the pyrolysis process in wood has characteristic features depending on the temperature range. Water loss, accompanied by a permanent loss of strength, begins at temperatures below 100 °C. The chemical bonds in the wood are broken at temperatures over 100 °C, and the wood begins to char in the 100–200 °C range as steam and other volatile gases are produced, including carbon dioxide, formic acid, and acetic acid. Pyrolysis slowly begins at approximately 120 °C and accelerates the dehydration at approximately 200 °C.

As the temperature rises above 200 °C, pyrolysis further accelerates, and flammable, volatile gases are actively produced in the 300–450 °C range. Volatile gases and a char layer are produced during pyrolysis. The carbon layer predominates when the wood's internal temperature is below 300 °C, while volatile gases are the principal product when the temperature rises above 300 °C.

The boundary between the char layer and the residual cross-section is very clear, and the temperature at the boundary is approximately 300 °C. The remaining cross-section is the load-bearing portion of the structure and is responsible for maintaining the load-bearing capacity of wooden elements in the event of a fire [8]. Figure 1 shows the appearance of the char layer in a timber column exposed to fire.



(a) (b)

Figure 1. Charring layer of timber exposed to fire: (**a**) residual cross-section of timber column exposed to fire, and (**b**) cross-section of timber column after fire test.

2.2. Fire-Resistant Design of Wooden Structures

Wooden elements exposed to fire undergo pyrolysis, creating a char layer. During the required fire-resistance period, during which the elements must maintain their performance in the event of a fire, the char layer acts as a fire-resistant insulator and thus protects the remaining cross-section. The remaining cross-section, which ensures the load-bearing capacity, is calculated from the structural design, and the final cross-section is calculated based on the charring depth, ensuring the required fire-resistance period. Stated differently, the design of wooden structures that withstand fire requires an estimation of the char layer, with the charring depth determined by the rate of charring and the length of time that the structure is exposed to fire.

In South Korea, there is an accreditation system for fire-resistant structures to ensure the fire-resistant performance of elements. Under this system, wooden structural elements must demonstrate their performance through fire tests, using the charring depth recognized for fire-resistant structures. Despite this system, there are no specific regulations in South

Korea for calculating charring rate or charring depth. Conversely, the charring depth of wood overseas is calculated from the charring rate and used in fire-resistant construction.

According to a study conducted by Buchanan and Abu [6], when the wood is exposed to a fire and the temperature rises above a certain level, burning occurs, and when the cross-sectional width (b) $\times$ length (d) of the timber is reduced by the fire on the remaining section, $b_f \times d_f$, the charring depth of the exposed section is given by Equation (1), below:

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

where:

c = charring depth (mm),
β = charring rate (mm/min), and
t = time (min).

As shown in Figure 2, after the char layer is formed, the residual cross-section can be determined, as shown in Equations (2) and (3):

$$b_f = b - 2c, \tag{2}$$

$$d_f = d - 2c \text{ (heating of 4faces)}, \tag{3}$$

where:

b_f = width of the residual section, and
d_f = length of the residual section.

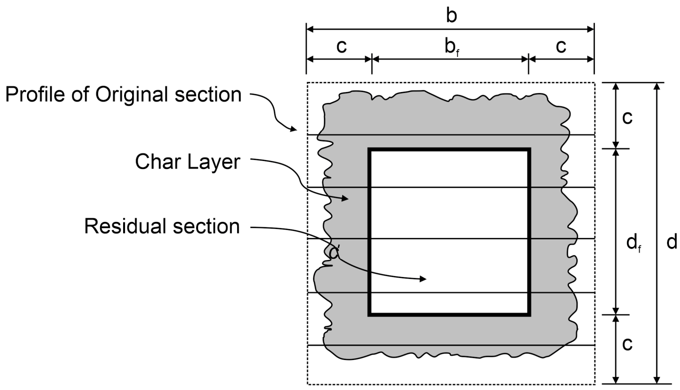


Figure 2. Design concept for fire-resistant timber members.

In the European design standards for wooden structures (Euro code) [9], the proposed char depth model for timber is the same as Equation (1), and the char rate, β, is determined from its relationships with char depth and time. Since approximately 10% more charring occurs at the corners of timber sections compared to the rest of the section, the Euro code design standards for wood structures specify both the general charring rate (β_0) and the notional charring depth (β_n), which is responsible for corner charring. Table 1 summarizes the charring rates for wood suggested in the Euro code.

Table 1. Charring rates β_0 and β_n of timber for design purposes.

Material	Minimum Density (kg/m^3)	Charring Rate	
		β_0 (mm/min)	β_n (mm/min)
Glue-laminated softwood timber	290	0.65	0.70
Solid or glue-laminated hardwood timber	450	0.50	0.55

3. Fire Test Methods

3.1. Summary of Fire Tests

During the fire tests for glued laminated timber columns, both load-bearing and non-load-bearing tests measuring the charring depth were performed. Glued laminated timber samples were manufactured using Korean larch into columns with a 300 mm^2 cross-section and a height of 3000 mm.

The fire tests were performed in accordance with Korean industrial standards KS F 2257-1 (Fire-resistance test methods for structural elements—general requirements) [10] and KS F 2257-7 (Fire-resistance test methods for structural elements—performance requirements for columns) [11]. Accordingly, the size of the specimen must have a minimum length of ≥3 m and a height of ≤300 mm. Therefore, the specimen was manufactured on a full scale according to the corresponding standard [11].

For the fire temperature curve, the standard time–temperature curve (ISO 834-1) [12] was used, and the charring depth of the samples and displacement during the load-bearing tests were measured. Figure 3 shows the standard time–temperature curve (ISO 834-1) [12].

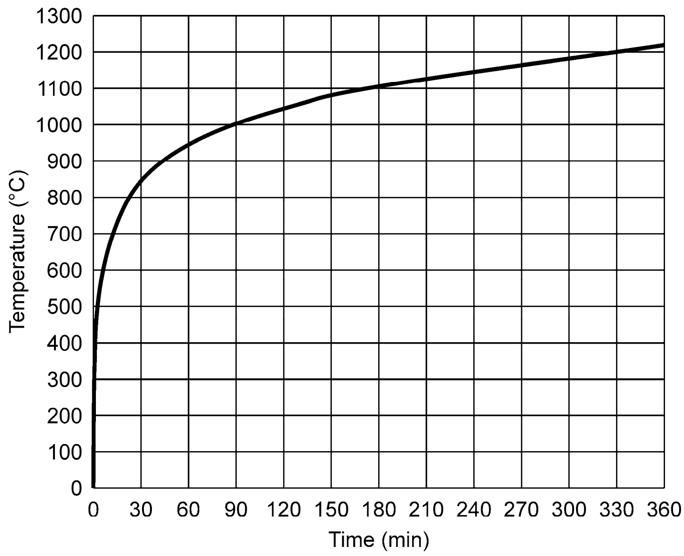
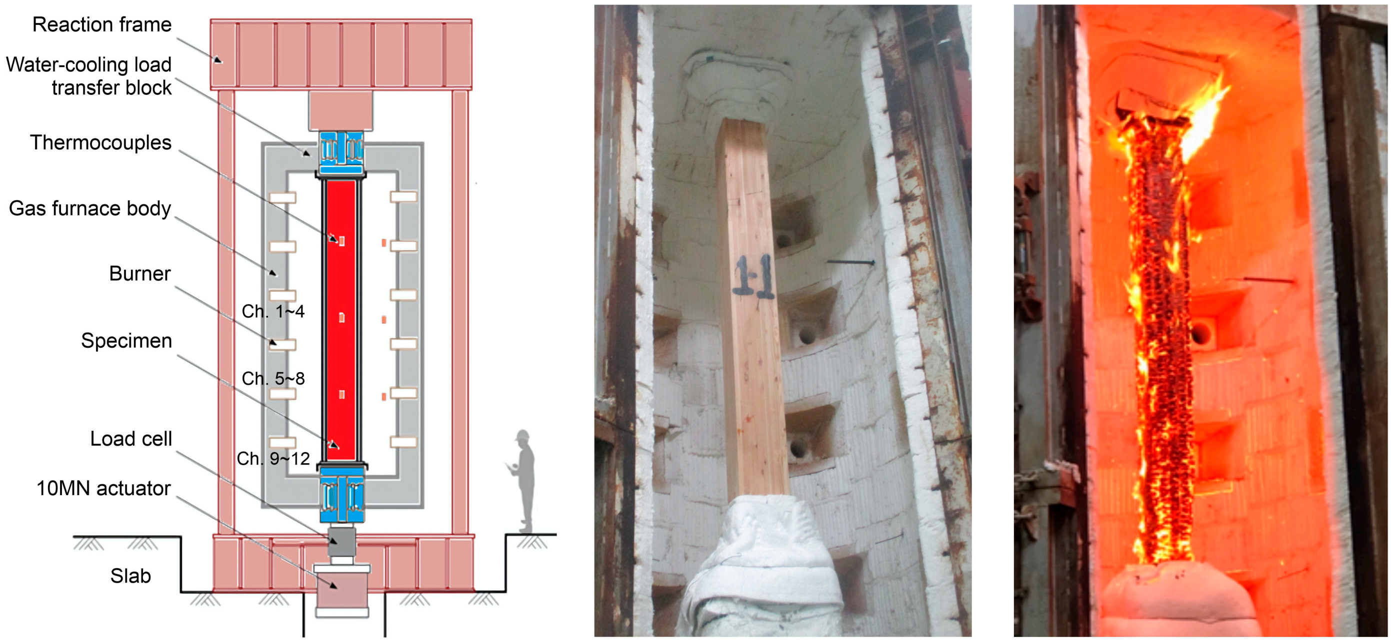


Figure 3. Standard time–temperature curve (ISO 834-1).

The fire test furnace used liquefied natural gas as fuel, and the loading apparatus applied a load to the bottom of the samples via a hydraulic device at the bottom of the furnace. Figure 4 shows the column fire test furnace, the placement of a sample, and a photograph of a fire test. The column fire test furnace was closed on all four sides during the tests, and the hydraulic actuator for the load-bearing tests was placed at the bottom of the furnace. The fire tests lasted for a total of two hours. The displacement of the samples was measured in the load-bearing test. For the non-load-bearing test, the displacement was omitted and whether the samples had fire resistance was determined. The samples were tested under different loading conditions of the load calculated from the residual cross-section. Since the fire tests were performed in a closed furnace, the samples were exposed to high temperatures on all four sides.

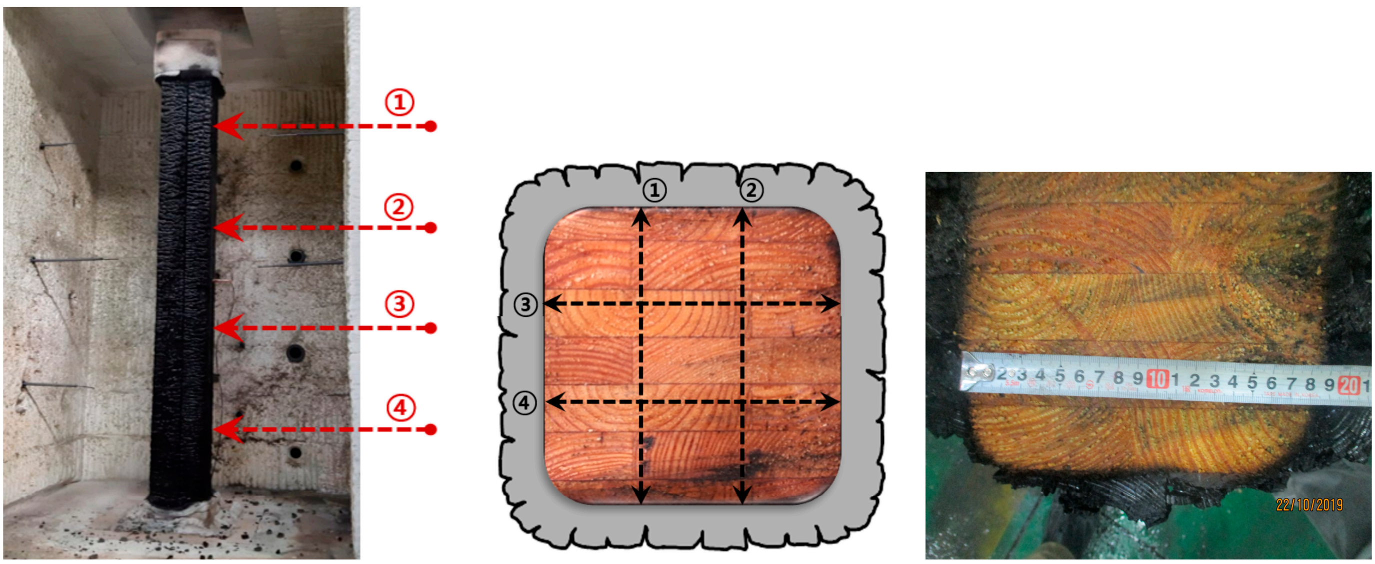
3.2. Measurement of Charring Depth

In this study, the measurement was conducted only for the residual section without considering the zero-strength layer. The charring depth of the samples was measured in sections spaced at four even intervals along the length of the columns. Measurements were taken at four locations in each section so that char depth was measured a total of 16 times for each sample. Figure 5 shows the locations of char depth measurements on the column in each section.



(**a**) (**b**) (**c**)

Figure 4. Design concepts for fire-resistant timber members: (**a**) column fire test in furnace, (**b**) sample before fire test, and (**c**) sample after fire test.



(**a**) (**b**) (**c**)

Figure 5. Charring depth measurement of sample: (**a**) measurement location after fire test, (**b**) charring depth measurement point, and (**c**) charring depth measurement.

3.3. Fire Tests for the Glued Laminated Timber Columns

To examine the charring characteristics of the glued laminated timber, changes in the charring depth were examined under various conditions. Since columns, as an important structural element of buildings, are typically load-bearing elements, changes in charring properties were observed, such as charring depth and charring rate, under different load conditions. To examine the charring characteristics under load, the results of the load-bearing fire test and non-load-bearing fire test were also compared.

For the charring rate used in the calculation of the residual cross-section and to calculate the load in the load-bearing fire test, the design values suggested in the Euro code were used. Based on the load corresponding to the calculated residual cross-section, 120 min fire tests were performed using load ratios in the range from 0.5 to 1.3. The fire test samples were made with the same dimensions and named according to the load ratio. The carbonization rate, refractory time, and a safety factor of 10% of the EN code were applied to derive the allowable load value. Based on this ratio, a load value of 0.5–1.3 was determined.

To investigate the charring characteristics over time, the non-load-bearing fire tests were conducted with durations ranging from 30 to 120 min at 30 min intervals. Like the load-bearing fire tests, all samples were produced with the same standards and named according to the test duration.

In South Korea, when measuring charring depth for fire-resistance certification, a 10% safety factor is added to the measured value, irrespective of corner rounding; therefore, the same criteria was applied when calculating the residual cross-section. The samples were made with a density of 290–450 kg/m^3; therefore, a charring rate of 0.65 mm/min was used, which is recommended as β_0 in the Euro code. Although the general charring rate, β_0, was used, it was assumed that the results were similar to those using the notional charring rate, β_n, because the 10% safety factor was considered. When calculating the test loads, the calculated charring depth of 85.8 mm was used.

Table 2 shows a summary of the glued laminated timber column fire test samples fabricated from South Korean larch and the test results.

Table 2. Fire resistance test samples and test results.

Specimen	Specimen Size (mm) (W × D × H)	Test Time (min)	Fire-Resistant Time (min)	Test Load (kN)	Load Ratio	Displacement (mm)	Charring Depth (mm)
C-L-1	300 × 300 × 3000	120	116	218.7	1.3	33.12	89.5
C-L-2			120	151.4	0.9	2.16	87.4
C-L-3			120	117.7	0.7	3.01	87.5
C-L-4			120	100.9	0.6	0.52	87.8
C-L-5			120	84.1	0.5	2.87	87.8
C-NL-1		30	30	-	-	-	21.8
C-NL-2		60	60				40.5
C-NL-3		90	90				57.5
C-NL-4		120	120				77.1

Specimen Name: C(Column)-L (Load-bearing fire test)-1–5 (Load ratio 1.3–0.5); C(Column)-NL (Non-load-bearing fire test)-1–4 (Test time 30–120 min).

To determine whether the samples met the fire-resistance performance criteria, the displacement proposed in KS F 2257-1 [10] was used as a load-bearing capacity criterion. The displacement criteria are shown in Equation (4) below:

$$\delta = \frac{h}{100}\,mm = \frac{3000}{100} = 30\ mm \tag{4}$$

where h = sample height before test (mm).

4. Results and Discussion

4.1. Change in Displacement

The load-bearing fire tests were conducted for 120 min. Only sample C-L-1 exceeded the performance criterion at 117 min and showed fire resistance up to 116 min. The remaining samples all satisfied the criteria for load-bearing fire resistance for 120 min.

For the results of the load-bearing fire test, the displacement and change in charring depth at different load ratios were the focus. The displacement measured for all samples satisfied the performance criteria and showed very stable behavior, except for C-L-1, which did not demonstrate load-bearing fire resistance. For column elements subjected to compressive loads, it is normal for higher load ratios to increase displacement; however, the samples in this study did not show significant differences in displacement behavior. Figure 6 demonstrates the changes in displacement over time in the load-bearing fire tests.

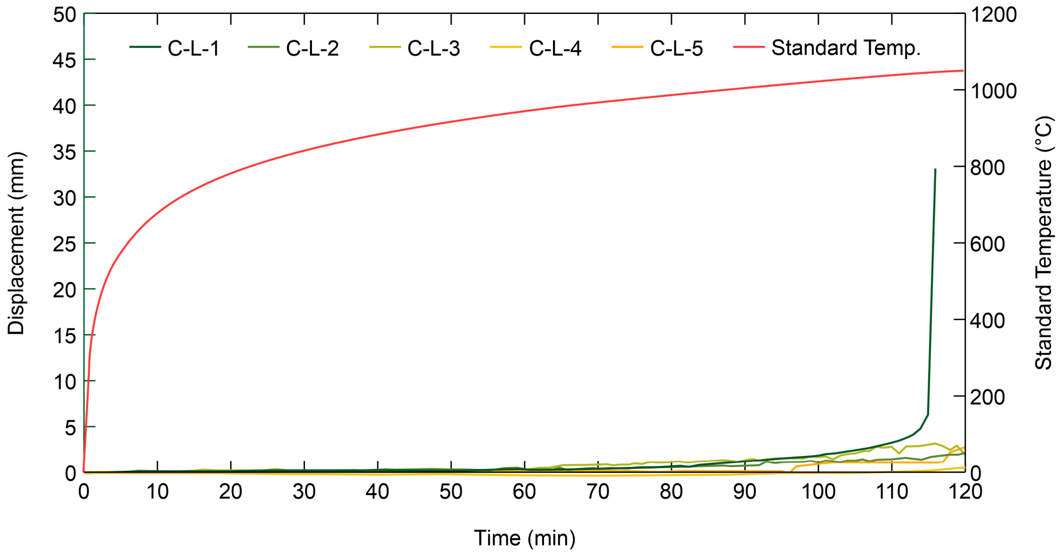


Figure 6. Behavior of samples with a time displacement.

The compression behavior of the glued laminated timber columns differed from that of typical vertical elements, which is thought to be due to differences in the method of calculating load. When calculating test loads for column elements, the load is usually calculated for the entire cross-sectional area of the samples. However, since only the residual section provided structural resistance and a char layer formed in the glued laminated timber in this experiment, the char layer was omitted and only the residual section was used as the valid cross-sectional area when calculating the load. In other words, compared to normal samples with the same cross-sectional area, the valid area responding to external loads, represented by the residual section, was smaller for the glued laminated timber samples. During the fire tests, the structurally valid cross area was protected from damage by the char layer, which prevented the transfer of high temperatures inside the furnace.

Although the structural cross-section of normal column elements was damaged at the same time as the fire test, the glued laminated timber columns' structural cross-section suffered minimal damage because it was continually protected by the char layer. This difference could explain why the load had a minimal effect on displacement at load ratios where the test load was smaller than the designed external forces. To show stable results in the fire test, at a load ratio of 1.3, the samples need a residual section wider than the valid residual section calculated when determining the test load. However, the section beyond the calculated valid residual section underwent pyrolysis and was charred, making it unable to resist the load. Therefore, when the threshold of the actual required residual section began charring, the samples showed rapid brittle failure and a sharp increase in displacement.

4.2. Change in Charring Depth at Different Load Ratios

Load-bearing fire tests were performed at load ratios ranging 0.5–1.3, and the effects of different load ratios on charring depth were examined. Table 3 provides the results of the load-bearing fire tests, with emphasis on load ratio and charring depth.

Table 3. Load-bearing fire test results of charring depth.

Specimen	Load Ratio	Charring Depth (mm)	Euro Code (β_0) Charring Depth (mm)	Euro Code (β_n) Charring Depth (mm)	Average Charring Depth (mm)
C-L-1	1.3	89.5	78.0	84.0	88.0
C-L-2	0.9	87.4			
C-L-3	0.7	87.5			
C-L-4	0.6	87.8			
C-L-5	0.5	87.8			

At different load ratios, charring depths were observed in the range of 87.4 to 89.5 mm. The empirically measured charring depths were compared with the estimated charring depths based on the Euro code, using the test load values (adding a 10% safety factor). A 12% difference in the general charring rate, β_0, and a 4% difference in the notional charring rate, β_n, were observed. It is believed that the charring depth in the load-bearing fire tests was deeper than the values specified in the Euro code because the load applied to the samples caused part of the charred layer to fall off during the test, causing the pyrolysis threshold to be shifted accordingly. Notably, the charring depth was closer to the notional charring rate, β_n, which accounts for corner rounding, than to the general charring rate, β_0.

Figure 7 shows the charring depth measured at 16 locations in each of the load-bearing fire test samples. Here, only C-L-1, which did not have satisfactory fire resistance, shows local variations in charring depth. In other samples, the charring depth shows consistent behavior at every location. Specimen C-L-1, which had the highest load ratio of 1.3, experienced delamination of the carbon layer due to the applied load during the fire resistance test. Consequently, a new heating surface was formed in the area where the carbon layer was removed, and additional carbonization occurred. Therefore, the graph shape shown in Figure 7 appeared owing to the uneven carbonization thickness caused by the load.

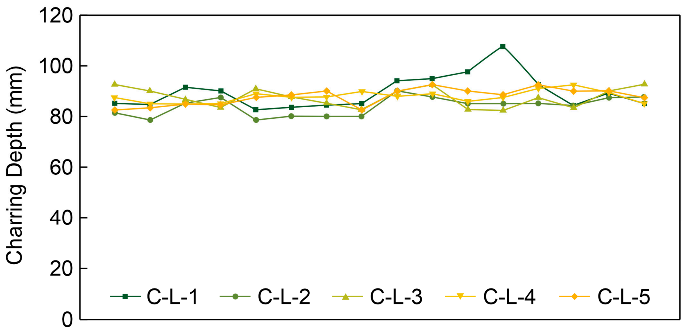


Figure 7. Behavior of samples at charring depth.

As shown in Figure 8, which illustrates the change in charring depth at different load ratios, the charring depth was mostly stable at load ratios of ≤0.9. In other words, at loading ratios of ≤0.9, the loading ratio had a minimal effect on the charring depth. This effect is consistent with the pattern observed for displacement changes under different load ratios.

As shown in the results of the fire resistance duration and displacement in the load-bearing fire tests, at load ratios of ≤0.9, there was almost no damage to the valid residual cross-section, calculated based on the char layer. This result means that the load-bearing strength of the residual section was maintained, and this maintained strength is considered the main reason why the load ratio did not affect charring depth. In Figure 8, comparing load ratio and displacement, there was a rapid increase in displacement from a load ratio of 0.9; however, at load ratios of ≤0.9, the displacement was relatively stable.

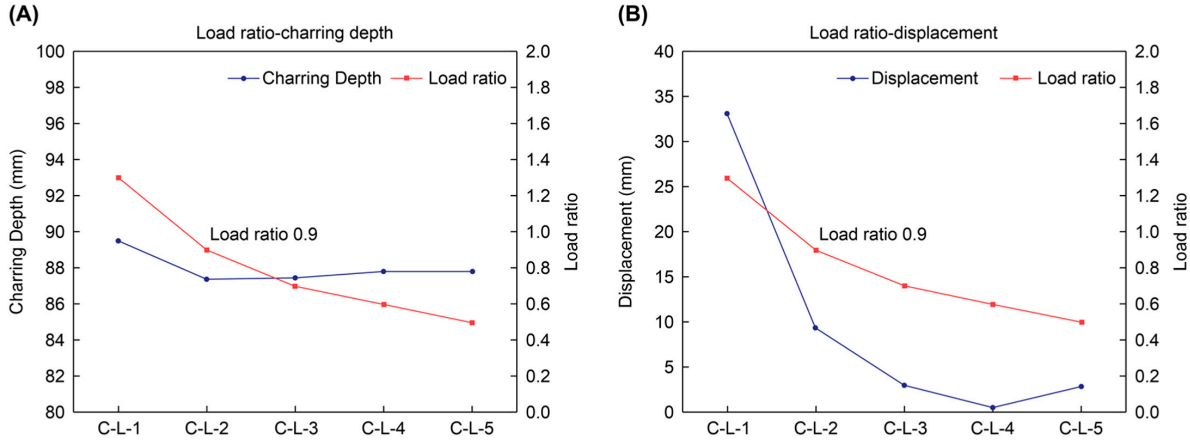


Figure 8. Behavior of samples by load ratio: (**A**) load ratio-charring depth, and (**B**) load ratio-displacement.

4.3. Change in Charring Depth over Time

Non-load-bearing fire tests were performed for various durations at 30 min intervals up to 120 min, and the effects of test duration on charring depth were examined. Table 4 shows the results of the non-load-bearing fire tests, focusing on time, charring depth, charring rate, and the Euro code.

Table 4. Non-load-bearing fire test results of charring depth and charring rate.

Specimen	Test Time (min)	Charring Depth (mm)	Charring Rate	Euro Code (β_0) Charring Depth (mm)	Euro Code (β_0) Charring Rate	Euro Code (β_n) Charring Depth (mm)	Euro Code (β_n) Charring Rate
C-NL-1	30	21.8	0.648	19.5	0.65	24.0	0.70
C-NL-2	60	40.5		39.0		48.0	
C-NL-3	90	57.5		58.5		72.0	
C-NL-4	120	77.1		78.0		96.0	

Based on the results for charring depth over time, a charring rate of 0.648 min/mm (r^2 = 0.997) was observed. The difference between the estimated charring depth based on the Euro code and the observed charring depth was 0.3% at the general charring rate, β_0, and 8% at the notional charring rate, β_n. Unlike the load-bearing fire tests, because there was no effect of load on the samples in the non-load-bearing fire tests, the observed charring depth was similar to that estimated using the general charring rate, β_0, in the Euro code.

Since the results for samples manufactured using South Korean larch were measured values and did not account for any safety factors, they were similar to the charring rate suggested in the Euro code. Figure 9 compares the test results with the Euro code.

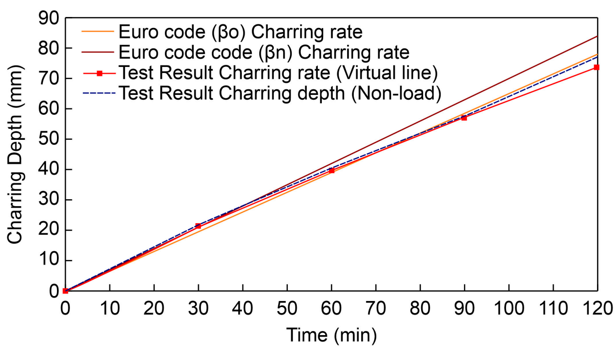


Figure 9. Test results of charring depth and virtual line Euro code.

4.4. Differences in Charring Depth Between the Load-Bearing and Non-Load-Bearing Fire Tests

Table 5 shows a summary of the results for char depth in the 120 min load-bearing and non-load-bearing fire tests.

Table 5. Samples and test results for fire resistance.

Specimen	Specimen Size (mm) (W × D × H)	Test Time (min)	Load Ratio	Charring Depth (mm)	Charring Rate
C-L-1	300 × 300 × 3000	120	1.3	89.5	0.75
C-L-2			0.9	87.4	0.70
C-L-3			0.7	87.5	0.73
C-L-4			0.6	87.8	0.73
C-L-5			0.5	87.8	0.73
			Average	88.0	0.73
C-NL-4			-	77.1	0.64

There was a difference of approximately 13% between the mean charring depths of the 120 min load-bearing fire tests and that of the non-load-bearing fire test. As explained in Section 4.2, when fire tests were performed under load, the compressive forces applied to the samples may have caused some of the char layers to fall out during the test. In this case, the pyrolysis threshold shifted relative to the new edge, which likely led to a deeper charring depth than in the non-load-bearing fire tests.

5. Conclusions

Glued laminated timber column elements were manufactured from South Korean larch and subjected to load-bearing fire tests, in which a vertical compressive force was applied to the samples, and non-load-bearing fire tests. The following results regarding the charring characteristics were derived.

First, in the load-bearing fire tests, very similar behavior (4% difference) was observed in the char depth estimated using the notional char rate in the Euro code, which accounts for the effects of corner rounding. This observation shows that corner rounding should also be considered when evaluating the char depth for glued laminated timber in South Korea. Currently, a safety factor of 10% is applied when certifying the fire-resistant structure of glued laminated timber in South Korea. However, this approach lacks logical evidence, while the corner rounding approach, which has the same effect, is based on more scientific evidence.

Second, in glued laminated timber, the char layer continuously protects the remaining section during the fire-resistance period, meaning the remaining section, i.e., the structure that provides resistance to external forces, is minimally damaged. Therefore, when external forces with a load ratio of $\leq$0.9 (i.e., less than the residual section's stress resistance) were applied, the load ratio had minimal influence on the displacement.

Third, the relationship between the load ratio and char depth was examined, and the load ratio had minimal influence on char depth at load ratios of $\leq$0.9. This minimal influence is likely because at loading conditions where the valid residual section (calculated based on the char depth) was almost not damaged, the resistance of the residual section to the loading was maintained, and therefore, the loading ratio had no significant influence on the char depth.

Fourth, when the results of the load-bearing and non-load-bearing fire tests were compared, the charring rate and charring depth were approximately 13% higher in the load-bearing fire tests. Since loading must also be considered when handling glued laminated timber, tests under harsher conditions than those for non-load charring are necessary, along with methods that apply a safety factor to the residual cross-section. In the load-bearing fire test, the application of vertical compressive force caused the detachment of the carbon layer during the fire test, leading to pyrolysis reoccurrence at the critical interface. This characteristic allows for the formation of a thicker carbon layer compared to a non-load-bearing fire test.

The scope of this study was laminated lumber using Korean larch. Although there are limits in GLT from Korean larch, most of the collection material in Korea is made using larch. Regarding building materials, the regional characteristics of wood cultivation affect the material properties of wood. This study provides data that can be used to compare the charring properties of laminated wood from South Korean larch with the charring properties, including charring rate, in foreign standards. These results provide useful reference data for developing fire-resistant design standards for timber structures made from South Korean timber in the future.

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