



Applicability of National Design Specification (NDS)-based 1-h Structural Fire Design to Korean Larch Glue-Laminated Beams: An Experimental Study

Sanghyun YOU¹ · Kyung-Sun AHN² · Jung-Kwon OH^{2,3,†}

ABSTRACT

This study evaluated the applicability of a 1-h structural fire design for glue-laminated timber (GLT) beams made of Korean larch using the methodology of the National Design Specification. The primary distinction between current South Korean industrial standards and the approach adopted in this study lies in the application of design stress adjustment factors and the zero-strength layer concept. To validate this methodology, the structural integrity of homogeneous GLT beams was evaluated through load-bearing fire resistance tests under three-sided fire exposure. The results support the applicability of the proposed fire design, as all the specimens maintained their structural integrity for the entire duration. Furthermore, the results provided additional insights into the charring behavior of GLT beams. The observation of more accelerated charring in the depth direction than in the width direction suggests the necessity of reestablishing the reference charring depth, accounting for factors such as the adhesive type and lamination configuration. Although all the specimens exhibited unexpected charring profiles—specifically, near four-sided charring in HG-1 and HG-2 and a T-shaped residual cross section in HG-3—their performances validated the robustness of the proposed design. HG-1 and HG-2 confirmed the safety of the proposed design under thermal conditions that were more severe than intended, whereas HG-3 demonstrated an enhanced safety margin inherent in real-world structural assemblies, such as beams integrated with floor members or gypsum boards. All the specimens successfully sustained the target loads for a duration of 1 h, verifying the reliability of the proposed design approach.

Keywords: structural fire design, glue-laminated timber, larch, charring depth, zero-strength layer, National Design Specification (NDS) adjustment factor, fire test

1. INTRODUCTION

The acceleration of climate change is prompting the industrial sector to reduce carbon dioxide (CO₂) emissions. The building sector accounts for 34% of global CO₂ emissions, with key materials such as cement and

steel contributing approximately 18% of these emissions while serving as major sources of construction waste (United Nations Environment Programme, 2025). The demand for building products with low embodied energy is steadily increasing, and the use of timber products is a viable solution. In South Korea, efforts to utilize local

Date Received March 20, 2026; Date Revised April 13, 2026; Date Accepted April 27, 2026; Published September 25, 2026

¹ Wood Engineering Division, National Institute of Forest Science, Seoul 02455, Korea

² Department of Agriculture, Forestry and Bioresources, Seoul National University, Seoul 08826, Korea

³ Research Institute of Agriculture and Life Sciences, Seoul National University, Seoul 08826, Korea

[†] Corresponding author: Jung-Kwon OH (e-mail: jungoh@snu.ac.kr, <https://orcid.org/0000-0002-8776-0955>)

© Copyright 2026 The Korean Society of Wood Science & Technology. This is an Open-Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/4.0/>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

timber resources for building members continue (Ahn *et al.*, 2021; Jang and Lee, 2019; Kim *et al.*, 2024, 2025a; Lee *et al.*, 2021, 2022; Pang and Jeong, 2019; Song and Kim, 2023; Yang *et al.*, 2021). In particular, timber building technology has been developed to satisfy the requirements of mid/high-rise buildings, and one of the main requirements is the safety of structures during fire events.

Although timber is a combustible material, it possesses unique self-protecting properties that render it a reliable structural material under fire conditions. When exposed to heat, timber develops an outer char layer that acts as an insulator, protecting the inner core and enabling it to maintain its structural integrity. Therefore, understanding the charring characteristics of timber products is crucial to structural fire design. The lignin, cellulose, and hemicellulose, which are the main constituents of wood, undergo thermal decomposition at high temperatures (200°C–500°C; Myung *et al.*, 2004), and it is well-known that the charring layer of timber members formed at 280°C–300°C loses its load-bearing capacity (Lucherini *et al.*, 2025; Qin *et al.*, 2021). Kim *et al.* (2025b) experimentally investigated the charring properties of cross-laminated timber (CLT) wall panels made of *Larix kaempferi*. The charring behavior accelerated as fire exposure progressed; the average charring rate was 0.87 mm/min for 1 h of exposure, which increased to 1.02 mm/min for 3 h of exposure. This study also evaluated the effect of the adhesive type on the charring behavior of a CLT wall panel. Within 2 h of fire exposure, panels bonded with polyurethane (PUR) resin adhesive exhibited a higher charring rate (0.94 mm/min) than those bonded with phenol-resorcinol-formaldehyde (PRF) resin adhesive (0.59 mm/min). Similarly, Choi *et al.* (2023) investigated the effect of the adhesive type on the charring rate of glue-laminated timber (GLT) columns made from *Larix kaempferi*. The results showed that specimens with PUR adhesive had a charring rate of 0.90 mm/min, which was 12.5% and

18.4% higher than those of resorcinol- and melamine-based GLT specimens, respectively. The bonding performance of adhesives has been reported to degrade at elevated temperatures (Frangi *et al.*, 2004; George *et al.*, 2003; Yang *et al.*, 2009), triggering the delamination of the char layer, which subsequently accelerates the charring rate and fire spread within the timber elements.

The National Design Specification (NDS; American Wood Council, 2018) and Eurocode 5 (CEN, 2004) adopt a structural fire design based on the actual load-bearing capacity of timber products. The load-bearing capacity is calculated from the residual cross-section, excluding the charring and zero-strength layers, as these are considered to have no significant strength or stiffness. The zero-strength layer, which has an insignificant structural capacity despite the uncharred layer, as reported by Schaffer (1986), is also considered when determining the effective cross section for structural fire design. Although the zero-strength layer is difficult to distinguish visually, it is included to account for the fact that the actual performance of a member is lower than the predicted structural performance of the residual cross-section when only the charring layer is excluded. Another difference is the adjustment of the design strength in fire situations. Owing to the high variation in strength, the characteristic strength of a timber member is generally determined based on the 5th lower percentile of the design value under normal conditions. However, Norén (1988) found that timber members exposed to fire exhibit lower strength variations than those tested at ambient temperatures. This conclusion was based on comparative tests in which all the beam specimens were sourced from the same timber. Based on the experimental results, Eurocode 5 adjusts the 5th percentile strength for the normal-temperature design to the 20th percentile value for fire design. This adjustment also reflects the relatively low probability of severe fire events (Buchanan and Abu, 2017). Meanwhile, the NDS adjusts the 5th percentile strength to the average value

with a design stress-to-member strength factor of 2.85. Although the adjustment of the design strength in Eurocode 5 seems more conservative, the current fire design of timber members in NDS follows the allowable strength design and requires structural calculations for full dead and live loads, whereas Eurocode 5 applies the reduction factor to the design load in a fire situation. Fire performance estimations based on the NDS are known to be more conservative than those based on other codes (Buchanan and Abu, 2017).

However, the rules on the standards for things like building evacuation and fireproof structures in South Korea (Ministry of Land, Infrastructure and Transport, 2025) strictly limit the application of structural members to areas for which fire performance has been verified through standardized tests, which are typically conducted by designated testing agencies. Among timber products, only GLT members are currently permitted for use in structures requiring fire resistance ratings (Korean Standards Association, 2013). Under the current criteria, approval is granted only to GLT products with a cross-sectional area that has increased by an amount equivalent to the expected charring depth. However, simply increasing the member dimensions by the expected charred area is primarily form of sacrificial fire protection and does not represent a performance-based structural fire design. A critical issue is that the bending performance of the remaining residual cross-section must satisfy the same design requirements as in ambient conditions, including stringent serviceability limits such as deflection. This regulatory insistence on maintaining ambient-level serviceability during a fire event is excessively conservative, and deviates from the fundamental goal of preventing collapse. Furthermore, the relatively low stiffness of timber products amplifies this economic disadvantage, as GLT beams require much larger cross-sections to satisfy the serviceability requirements. Although the current method offers simplicity, a structural fire design for GLT members based on the actual

load-bearing capacity must be introduced to enhance the economic efficiency. This study aimed to evaluate the applicability of performance-based fire design by experimentally verifying the actual bending performance of GLT beams after 1 h of fire exposure.

2. MATERIALS and METHODS

2.1. Structural fire design of glue-laminated timber beam

Larch (*Larix kaempferi*) GLT beams with a 1-h structural fire design were produced. Eight laminae of the same grade (E10) were used to produce homogeneous GLT (HG) categorized as grade 7S-27B (Korean Standards Association, 2021). The gross specimen size was 150 mm × 200 mm × 4,700 mm [width (*b*), depth (*d*), and length (*L*), respectively]. Fire design should consider the charring characteristics and material properties which depend on the type of timber products and the species. The charring depth ($d_{char,n}$) of GLT made of larch species after 1 h of fire exposure on three sides has been calculated to be 40 mm, in accordance with KS F 1611-3 (Korean Standards Association, 2013). Because the zero-strength layer has not been addressed in the standard, a value of 0.3 inches (7.6 mm) was adopted for the depth of the zero-strength layer (d_0), as specified in the NDS (American Wood Council, 2018). Although the precise depth of the zero-strength layer remains the subject of ongoing debate, the NDS value was selected to maintain a conservative perspective (Buchanan and Abu, 2017). Accordingly, the effective char depth could be determined using Equation (1):

$$d_{char,eff} = d_{char,n} + d_0, \quad (1)$$

where $d_{char,eff}$ is the effective charring depth (mm), $d_{char,n}$ is the charring depth after 1 h (mm), and d_0 is the depth of the zero-strength layer (mm).

The adjusted bending design value for fire (f_b) was calculated using Equation (2) with the adjustment factors from the NDS. Because the GLT specimen was loaded in bending about the x-x axis, a value of one was used for the flat use factor (C_{fu}), which includes the effect of bending about the y-y axis. The calculated volume factor (C_V) was given a value of 1.08 based on Equation (3), the initial dimensions of the specimen before the fire test, and the length of the bending member between the zero-moment supports (l), which was 4,000 mm. However, C_V , which only addresses the strength reduction with a higher probability of defect occurrence as the volume increases, should not exceed one. The beam stability factor (C_L), which considered the lateral support during the test, was set to one because the test specimen was supported by steel covers on the lateral sides of the GLT beam during the fire experiment. The design stress of the member strength factor (K) was considered in the calculation of f_b values for the GLT specimens. The calculated f_b was 2.85 times higher than the reference bending design (F_b) value (9 MPa) at an ambient temperature for the specimen grade used in this study (Korean Standards Association, 2021). Fig. 1 shows a summary of the structural fire design of a GLT beam after 1 h of fire exposure.

$$f_b = F_b \times K \times C_V \times C_{fu} \times C_L \quad (2)$$

where f_b is the adjusted bending design value in fire (MPa); F_b is the reference bending design value at ambient temperature (MPa); K is the design stress-to-member strength factor (2.85); C_V is the volume factor; C_{fu} is the flat-use factor; and C_L is the beam stability factor.

$$C_V = \left(\frac{6,400}{l} \right)^{1/10} \left(\frac{305}{d} \right)^{1/10} \left(\frac{130}{b} \right)^{1/10} \quad (3)$$

where C_V is the volume factor; l is the length of the

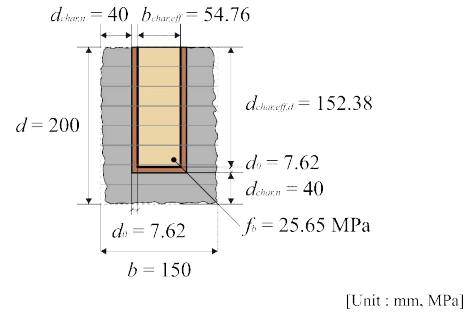


Fig. 1. One-hour structural fire design for GLT beams with three-sided charring exposure. Where b is the initial width, d is the initial depth, $d_{char,n}$ is the charring depth, d_0 is the zero-strength layer width, $b_{char,eff}$ is the effective width, $d_{char,eff}$ is the effective depth, and f_b is the adjusted bending design value for the fire. GLT: glue-laminated timber.

bending member between the points of zero moment (mm); d is the beam depth (mm); and b is the beam width (mm).

*Constants were adjusted to convert imperial units into SI units.

2.2. Experimental verification of structural fire design

The structural fire performances of the HG beams were experimentally verified using three test specimens (HG-1, HG-2, and HG-3). The size, grade, and species of the GLT beams were identical to those described in Section 2.1. The specimens were fabricated using laminae of E8 grade with a thickness of 25 mm and moisture content of less than 15%. A PRF resin-based adhesive was used for lamination. The fire tests were conducted in a horizontal furnace [Fig. 2(a)] at the Department of Fire Safety Research, Korea Institute of Civil Engineering and Building Technology (KICT, Hwaseong, Republic of Korea), following the general requirements of KS F 2257-1 (Korean Standards Association, 2019). A multi-burner system consisting of

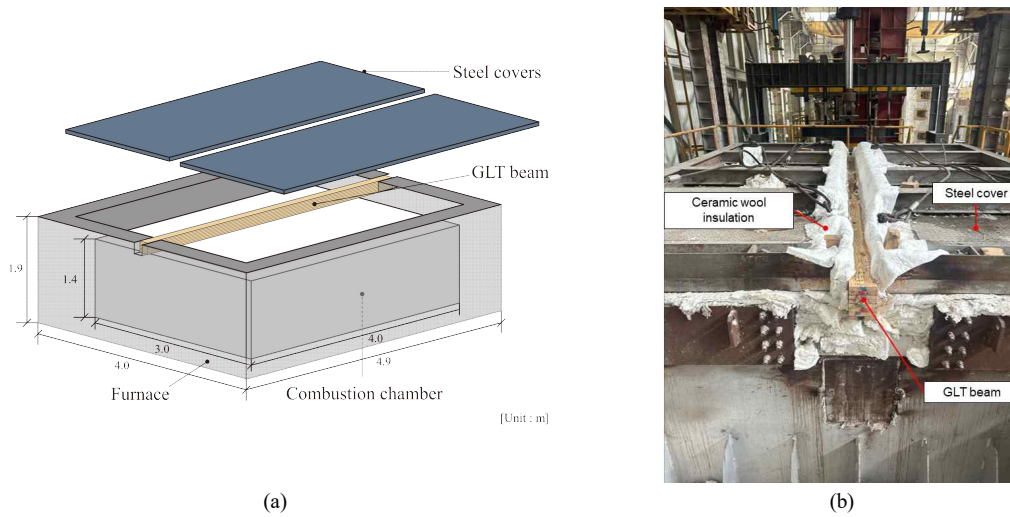


Fig. 2. Test set-up. (a) Layout of the test furnace with the combustion chamber and (b) a GLT specimen protected by ceramic wool insulation and steel covers. GLT: glue-laminated timber.

12 units was employed to control the internal temperature, with a total duty of 4,356,000 kcal/h (363,000 kcal/h per unit). Because the experimental verification was targeted at beams with three-sided fire exposure, the top surface of each GLT beam was covered with ceramic wool insulation, and steel covers for the entire furnace prevented flame spread [Fig. 2(b)]. The average temperature in the furnace was set according to Equation (4), which is widely accepted for fire testing (International Organization for Standardization, 2025). Steel covers were located on the side faces of the specimen, extending 50 mm downward from the top surface, and served as lateral supports along the entire span. The GLT specimens, which were supported at both ends of the furnace, were loaded with steel brackets and rectangular steel pipes [Fig. 3(a) and (b)]. The total applied load (P_s) was 8,160 N, which was calibrated to induce a tensile stress equivalent to f_b [Equation (5)]. Under these test conditions, the proposed structural fire design was validated by assessing the maintenance of its resistance to the applied load. After each test, the charring depth at the mid-span cross-section was measured to validate the

nominal charring depth specified in the current Korean standard. The charring depth in the width direction was measured at the glue line interfaces and mid-depth of each lamina. In the depth direction, the charring depth was measured at 5 mm intervals relative to the centerline of the specimen width (Fig. 4).

$$T = 345 \log(8t + 1) + 20, \quad (4)$$

where T is the average temperature in the furnace ($^{\circ}\text{C}$), and t is the heating time (min).

$$P_s = \frac{f_b \times b_{char,eff} \times d_{char,eff}^2}{3a}, \quad (5)$$

where P_s is the load imposed by the self-weight of the L-shaped steel brackets and pipe (N), f_b is the adjusted bending design value in fire (MPa), $b_{char,eff}$ is the effective width after 1 h of charring (mm; Fig. 1), $d_{char,eff}$ is the effective depth after 1 h of charring (mm; Fig. 1), and a is the distance from a support to a loading point (mm).

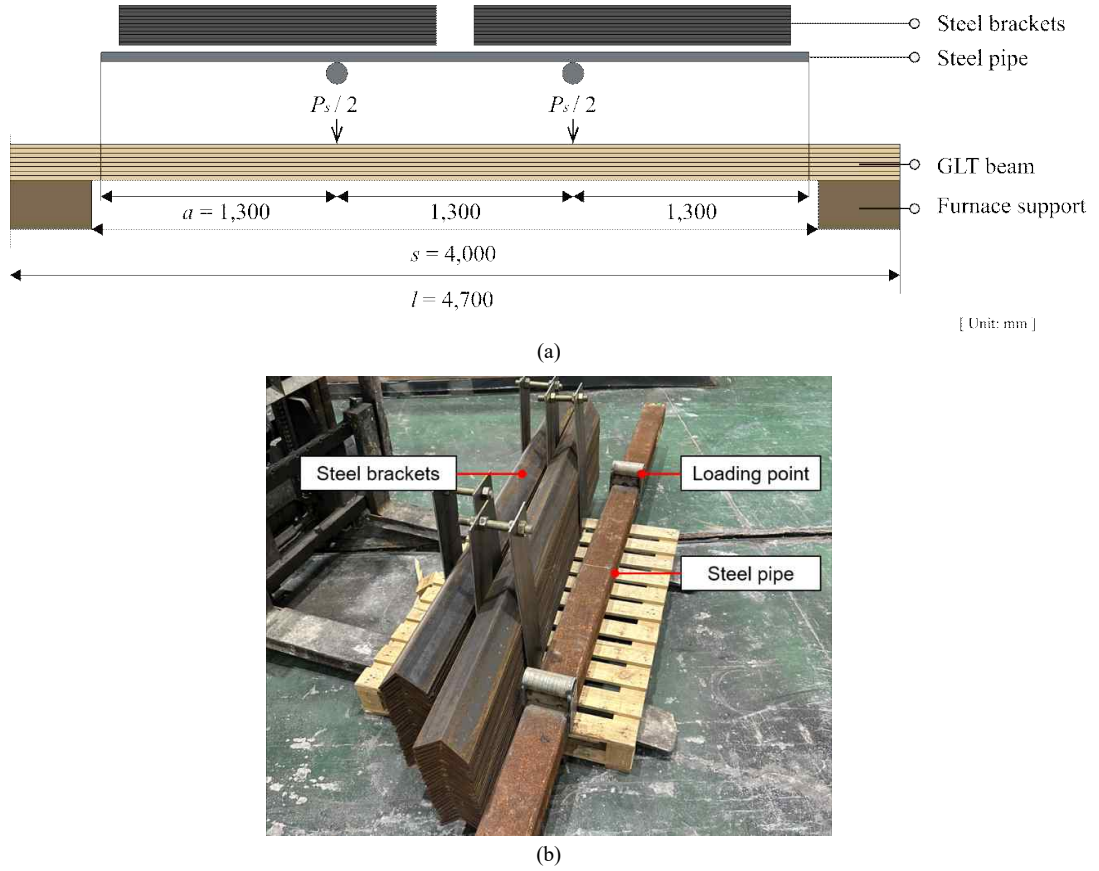


Fig. 3. Loading plan. (a) Structural layout of the fire test and (b) a picture of loading apparatus. GLT: glue-laminated timber.

3. RESULTS and DISCUSSION

The measured charring depths of each specimen are listed in Table 1. The results indicated that the mean charring value in the depth direction ($d_{char,n,mean}$) was generally greater than that in the width direction ($b_{char,n,mean}$). This accelerated charring in the depth direction is likely attributable to the thermal degradation of the bonding layers. This resulted in delamination of the laminae along with the charring layer, which prematurely exposed the underlying uncharred wood and deprived it of the protective insulation typically provided by the charring layer (Frangi *et al.*, 2004; George *et al.*,

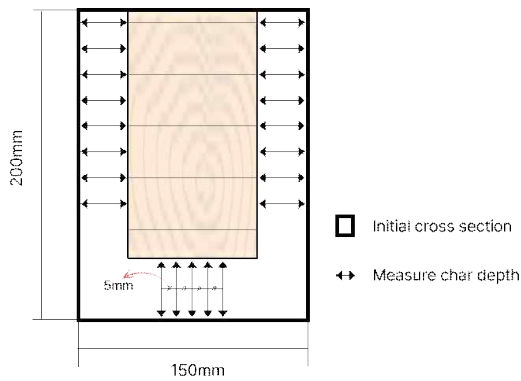


Fig. 4. Measurement of charring depth.

Table 1. Charring depths of GLT specimens

Specimen	b (mm)	d (mm)	$b_{char,n,mean}$ (mm)	$d_{char,n,mean}$ (mm)
HG-1	150	200	36.49 (0.07)	38.80 (0.06)
HG-2			36.97 (0.15)	42.05 (0.03)
HG-3			36.97 (0.10)	42.24 (0.03)

Here, b is the width of the specimen before the test, d is the depth of the specimen before the test, $b_{char,n,mean}$ is the mean charring depth along the specimen width, and $d_{char,n,mean}$ is the charring depth in the specimen.

GLT: glue-laminated timber, HG: homogeneous GLT.

2003; Yang *et al.*, 2009). Although this study utilized PRF adhesive, which is known to have better bonding performance under elevated temperatures than PUR adhesive, previous studies have reported a reduction in the bonding strength of the PRF adhesive at temperatures greater than 200°C (Bernaczyk *et al.*, 2023; Klippel, 2014; Liu *et al.*, 2020). In addition, the experimental evidence in this study suggests that the risk of thermal degradation of the bonding layer still remains. The increased charring value in the depth direction of the specimen also raised concerns regarding the adequacy of the nominal charring depth (t) specified in the current standards. Although the $b_{char,n,mean}$ values for all the HG specimens remained 7.6%–8.8% lower than the nominal charring depth of 40 mm, the $d_{char,n,mean}$ values for HG-2 and HG-3 specimens exceeded it by 5.1% and 5.6%, respectively. Furthermore, current standards do not differentiate between adhesive types despite the fact that PUR resin-based adhesives typically exhibit lower thermal stability than PRF-based adhesives. Therefore, to ensure the structural fire safety of timber systems, it is imperative to reestablish the nominal charring depth based on an expanded experimental database that accounts for adhesive performance. Although the results of this study suggest the potential influence of the adhesive layers on the charring behavior of GLT, the current experimental data were insufficient to fully isolate this effect. To verify the specific contributions of the adhesives, further fire tests on GLT beams with different lamination orien-

tations, such as horizontally and vertically laminated configurations, are required.

Contrary to expectations, the charring behavior of the test specimens deviated from the idealized behavior after three-sided fire exposure. Although the specimens were protected by ceramic wool insulation and steel covers, structural deflection during the test resulted in gaps between the specimen and insulation. Consequently, the top surfaces of the HG-1 and HG-2 specimens were exposed to the elevated furnace temperature, resulting in charring depth of 6.8 and 3.7 mm, respectively [Fig. 5(a) and (b)]. Such issues could become more pronounced as the span length increases, primarily owing to the relatively low stiffness of the timber, because the resulting gap allows for convective heat transfer into nominally insulated zones. The residual section of the HG-2 specimen exhibited a trapezoidal shape, in contrast to the profile of HG-1. This discrepancy was attributed to the maintenance of the insulation system. Specifically, the ceramic wool liners attached to the steel covers were replaced with new materials because the original liners deteriorated during the HG-1 test. The fresh ceramic wool provided better airtightness and more effectively shielded the upper surfaces from heat penetration. This enhanced protection restricted charring at the top corners, resulting in the observed trapezoidal residual section. The steel covers for HG-3 were extended to a depth of 100 mm to address unintended fire exposure at the top surface; however, in this case, the

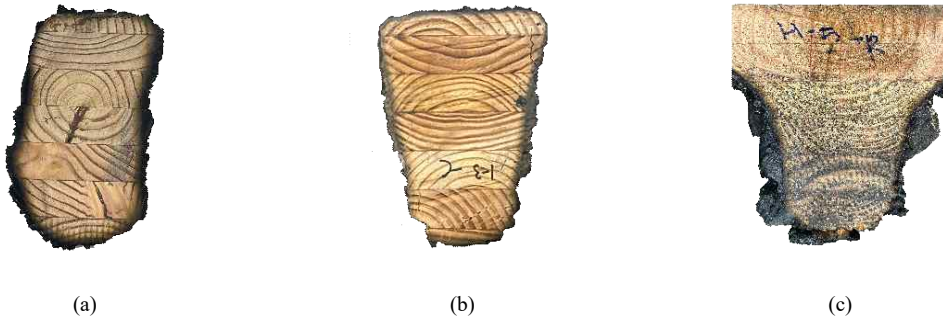


Fig. 5. Charring sections of specimens. (a) HG-1, (b) HG-2, and (c) HG-3. HG: homogeneous glue-laminated timber.

top two laminae were entirely protected from heat exposure, resulting in a T-shaped residual cross-section [Fig. 5(c)], which was inappropriate for verifying the proposed design method for three-sided charring.

Despite these unintended charring behaviors, the specimens sustained the target loads throughout the 1-h fire test without any observable fracture. The maximum tensile stress of the outer laminae (σ_t) of each specimen was estimated based on the experimental charring depths ($b_{char,n,mean}$ and $d_{char,n,mean}$). Subsequently, these values were compared with those derived from the structural fire design following the NDS (Fig. 1) and KS F

1611-3, as summarized in Table 2. The cross-sectional area of HG-3 was assumed to be an idealized T-shaped section. Although the charring layers at the top surfaces of the HG-1 and HG-2 series were included in the calculations, the σ_t values of the specimens remained lower than the reference design values specified by the NDS, albeit by a small margin. Despite the structural integrity of the specimens, the appropriateness of the fire design should be carefully verified because of the limited sample size. However, the potential uncertainties arising from the limited data are expected to be mitigated by a conservative F_b . Specifically, the metho-

Table 2. Comparison of geometries and estimated tensile stresses of GLT beams

Type	Section	$b_{char,eff}$ (mm)	$d_{char,eff}$ (mm)	I (10^3 mm ⁴)	y (mm)	M (Nmm)	$\sigma_{t,max}$ (MPa)
HG-1	Rectangular	61.8	146.8	13,874.3	69.6		23.9
HG-2	Rectangular	60.8	146.6	13,614.6	69.5		24.3
HG-3	Flange	150	50	25,593.6 ¹⁾	91.5	5,304,000 ²⁾	19.0
	Web	60.8	100.1				
Reference (Fig. 1)	Rectangular	54.8	152.4	16,146.0	76.2		25.0
KS F 1611-3	Rectangular	70	160	23,893.3	80.0		17.8

Here, $b_{char,eff}$ is the effective width, $d_{char,eff}$ is the effective depth, I is the moment of inertia, y is the neutral axis, M is the applied moment, and σ_t is the maximum estimated tensile stress in the outermost tensile lamina.

¹⁾ Total moment of inertia using the parallel axis theorem.

²⁾ $M = (P_s \times a) / 2$ [Fig. 3(a)].

GLT: glue-laminated timber, HG: homogeneous GLT.

dology of structural fire design primarily adopts NDS adjustment factors to determine f_b [Equation (2)], while maintaining the strength reduction factor for F_b mandated by the Korean standard. Because the strength reduction factor, which accounts for the effects of normal load duration and safety factors, is 42.9% higher than that of the NDS (American Society for Testing and Materials [ASTM], 2018), this inherent conservatism is considered to function as a robust safety margin. However, the results for the HG-3 specimen should not be regarded as a direct validation of the NDS structural fire design because the idealized three-sided exposure was not fully realized in the setup. Nevertheless, the experimental case of HG-3 effectively demonstrated the enhanced safety margin provided by realistic assembly conditions. The σ_t value of the HG-3 specimen was estimated to be 24.2% lower than the NDS value, highlighting the significant structural advantage of protecting the upper layers of the side surfaces of beams. This reflects common real-world structural applications in which the upper-side surfaces of timber beams are protected by floor slabs or gypsum boards. Ultimately, the fact that the estimated σ_t values of all the specimens significantly exceeded the values permitted by KS F 1611-3 demonstrated that the proposed design not only ensures structural reliability but also offers substantial economic advantages. By allowing for a more optimized and less overly conservative cross-sectional design compared to that based on the current Korean standards, this approach enables more efficient material use in GLT beam construction without compromising fire safety.

4. CONCLUSIONS

The experimental verification of a 1-h structural fire design based on the NDS for HG beams made of Korean larch led to the following conclusions.

- The experimental charring depth of the GLT

specimens in the depth direction was found to be 5.1%–5.6% higher than the nominal charring depth specified in the Korean standard. In contrast to the width direction (7.6%–8.8% lower than the nominal value), the accelerated charring in the depth direction was likely due to the thermal degradation of the adhesive, which prematurely exposed the uncharred timber and deprived it of the protective insulation provided by the char layer. The experimental results suggested that new reference values for the nominal charring depth should be established based on the charring direction and adhesive type.

- Specimens HG-1 and HG-2 maintained their structural integrity without failure even under unintended four-sided fire exposure. While concerns regarding reliability may persist because of the limited sample size, the inherent safety margin of the Korean standard is expected to mitigate potential uncertainties; notably, the strength reduction factor for F_b in Korea is approximately 42.9% higher than that of the NDS.

- The results for the HG-3 series revealed a discrepancy from the intended three-sided fire exposure owing to unintended shielding by the steel covers, which resulted in a T-shaped residual cross-section. Analytical estimation confirmed that the σ_t value of these specimens was 24.2% lower than that of the idealized three-sided reference. This 24.2% reduction is significant because it demonstrates that realistic assembly conditions—where the upper side surfaces of beams can be protected by floor members or gypsum boards—provide a substantial, inherent safety buffer.

- The successful maintenance of the structural integrity in all the tested GLT beams validated the practical reliability of the proposed fire design. Notably, the capacity of the specimens to sustain load levels that significantly exceeded the upper limits permitted by KS F 1611-3 demonstrated that the proposed methodology offers a more economically viable solution. By allowing for optimized cross-sectional dimensions without compromising fire safety, this approach enables enhanced

material efficiency in the design of Korean larch GLT beams compared with current domestic standards.

Although the current findings verified the safety of the 1-h fire structural design of Korean larch GLT beams following the NDS methodology, further research involving a greater number of specimens is necessary to consolidate the design values statistically. Such efforts are crucial for establishing a robust and standardized structural fire design framework that ensures the safety of mass timber construction.

CONFLICT of INTEREST

No potential conflict of interest relevant to this article was reported.

ACKNOWLEDGMENT

Not applicable.

REFERENCES

- Ahn, K.S., Pang, S.J., Oh, J.K. 2021. Prediction of withdrawal resistance of single screw on Korean wood products. *Journal of the Korean Wood Science and Technology* 49(1): 93-102.
- American Society for Testing and Materials [ASTM]. 2018. Standard Practice for Establishing Allowable Properties for Structural Glued Laminated Timber (Glulam). D3737-18. ASTM International, West Conshohocken, PA, USA.
- American Wood Council. 2018. National Design Specification for Wood Construction with Commentary (2018 edition). American Wood Council, Leesburg, VA, USA.
- Bernaczyk, A., Wagenführ, A., Terfloth, C., Lincke, J., Krystofiak, T., Niemz, P. 2023. Investigations into the influence of temperature on the tensile shear strength of various adhesives. *Materials* 16(18): 6173.
- Buchanan, A.H., Abu, A.K. 2017. *Structural Design for Fire Safety*. 2nd ed. John Wiley & Sons, Chichester, UK.
- Choi, Y.J., An, J.H., Baik, K.H. 2023. Comparative analysis of fire resistance in glued laminated timber: The impact of adhesives and surface direction. *Journal of the Korea Institute of Building Construction* 23(6): 761-772.
- European Committee for Standardization [CEN]. 2004. Eurocode 5: Design of Timber Structures: Part 1-2: General: Structural Fire Design. CEN, Brussels, Belgium.
- Frangi, A., Fontana, M., Mischler, A. 2004. Shear behaviour of bond lines in glued laminated timber beams at high temperatures. *Wood Science and Technology* 38(2): 119-126.
- George, B., Simon, C., Properzi, M., Pizzi, A., Elbez, G. 2003. Comparative creep characteristics of structural glulam wood adhesives. *Holz als Roh- und Werkstoff* 61(1): 79-80.
- International Organization for Standardization. 2025. Fire-resistance Tests: Elements of Building Construction: Part 1: General Requirements. ISO 834-1. International Organization for Standardization, Geneva, Switzerland.
- Jang, S.S., Lee, H.W. 2019. Lateral resistance of CLT wall panels composed of square timber larch core and plywood cross bands. *Journal of the Korean Wood Science and Technology* 47(5): 547-556.
- Kim, C., Han, S., Choi, S. 2025a. Proposal for column-beam joint system in Korean mid- and high-rise timber structures. *Journal of the Korean Wood Science and Technology* 53(4): 370-388.
- Kim, K.H., Lee, H.M., Lee, M. 2024. Evaluation of adhesive characteristics of mixed cross laminated timber (CLT) using yellow popular and softwood structural lumbers. *Journal of the Korean Wood*

- Science and Technology 52(1): 58-69.
- Kim, S., Choi, Y.J., An, J. 2025b. Charring behavior and properties of cross-laminated timber wall panels fabricated with *Larix kaempferi* harvested in Korea. Journal of the Korean Wood Science and Technology 53(5): 550-562.
- Klippel, M. 2014. Fire safety of bonded structural timber elements. Ph.D. Thesis, ETH Zurich, Switzerland.
- Korean Standards Association. 2013. Fire Resistance Performance for Elements of Building Construction: Part 3: Beams and Columns made of Structural Glued Laminated Timber. KS F 1611-3. Korean Standards Association, Seoul, Korea.
- Korean Standards Association. 2019. Methods of Fire Resistance Test for Elements of Building Construction: General Requirements. KS F 2257-1. Korean Standards Association, Seoul, Korea.
- Korean Standards Association. 2021. Structural Glue-laminated Timber. KS F 3021. Korean Standards Association, Seoul, Korea.
- Lee, H.W., Jang, S.S., Kang, C.W. 2021. Evaluation of withdrawal resistance of screw-type fasteners depending on lead-hole size, grain direction, screw size, screw type and species. Journal of the Korean Wood Science and Technology 49(2): 181-190.
- Lee, I.H., Kim, K., Shim, K. 2022. Evaluation of bearing strength of self-tapping screws according to the grain direction of domestic *Pinus densiflora*. Journal of the Korean Wood Science and Technology 50(1): 1-11.
- Liu, J., Yue, K., Xu, L., Wu, J., Chen, Z., Wang, L., Liu, W., Lu, W. 2020. Bonding performance of melamine-urea-formaldehyde and phenol-resorcinol-formaldehyde adhesive glulams at elevated temperatures. International Journal of Adhesion and Adhesives 98: 102500.
- Lucherini, A., Pitelková, D.Š., Mózer, V. 2025. Estimating the effective char depth in structural timber elements exposed to natural fires, considering the heating and cooling phase. Engineering Structures 323(Part A): 119255.
- Ministry of Land, Infrastructure and Transport. 2025. Rules on the Standards for Evacuation, Fireproof Structures, etc. of Buildings. Enforcement Decree of the Building Act. Ministry of Land, Infrastructure and Transport, Sejong, Korea.
- Myung, S.Y., Eom, Y.J., Dong, J.I., Park, Y.K., Kang, B.S., Jeon, K.J. 2004. Characteristics of thermal decomposition of major components of biomass isolated from wood. Journal of the Korean Industrial Engineering Chemistry 15(8): 896-900.
- Norén, J. 1988. Failure of structural timber when exposed to fire. In: Itani, R.Y. (ed), Seattle, WA, USA, Proceedings of the 1988 International Conference on Timber Engineering.
- Pang, S.J., Jeong, G.Y. 2019. Effects of density, temperature, size, grain angle of wood materials on nondestructive moisture meters. Journal of the Korean Wood Science and Technology 47(1): 40-50.
- Qin, R., Zhou, A., Chow, C.L., Lau, D. 2021. Structural performance and charring of loaded wood under fire. Engineering Structures 228: 111491.
- Schaffer, E.L. 1986. Strength Validation and Fire Endurance of Glued-laminated Timber Beams. United States Department of Agriculture, Washington, DC, USA.
- Song, D.B., Kim, K.H. 2023. Influence of composition of layer layout on bending and compression strength performance of larch cross-laminated timber (CLT). Journal of the Korean Wood Science and Technology 51(4): 239-252.
- United Nations Environment Programme. 2025. Global Status Report for Buildings and Construction 2024/2025. United Nations Environment Programme, Nairobi, Kenya.
- Yang, S.M., Lee, H.H., Kang, S.G. 2021. Research trends in hybrid cross-laminated timber (CLT) to

- enhance the rolling shear strength of CLT. Journal of the Korean Wood Science and Technology 49(4): 336-359.
- Yang, T.H., Wang, S.Y., Tsai, M.J., Lin, C.Y., Chuang, Y.J. 2009. Effect of fire exposure on the mechanical properties of glued laminated timber. Materials & Design 30(3): 698-703.