Effect of Intumescent Coating on the Charring Rate of Nail-laminated Timber

Sung-Jun Pang,[a] Kyung-Sun Ahn,[a] Min-Jeong Kim,[a] Sung-Wook Hwang,[b] Seog Goo Kang,[c] Hyo Won Kwak,[a,b] Hwanmyeong Yeo,[a,b] and Jung-Kwon Oh [a,b,]*

Intumescent coating was studied relative to the fire performance of nail-laminated timber. Three NLT specimens were coated with three different intumescent coating thicknesses (1, 2, and 3 mm) in even-numbered laminae and compared to uncoated NLT specimens. As a result of the coating, the internal temperature of the coated specimen increased more slowly than that of the uncoated specimen. The average charring rate of the intumescent coating specimen was reduced by 12.8% (1-mm thickness), 14.1% (2-mm thickness), and 15.4% (3-mm thickness) compared with the uncoated specimen. However, statistical analysis showed there was no significance between 1-, 2-, and 3-mm coating thicknesses. The combustion of wide surfaces of timber laminae between the plywood was delayed due to the coated plywood, and the timber laminae became a one-dimensional charring rate problem. Therefore, if even laminae are coated with an intumescent, then the NLT can be designed with a one-dimensional charring rate condition.

DOI: 10.15376/biores.17.4.5999-6018

Keywords: Wood products; Timber; Fire resistance; Intumescent coating; Charring rate; Nail

*Contact information: a: Department of Agriculture, Forestry and Bioresources, Seoul National University, Gwanak-ro 1, Gwanak-gu, Seoul, Republic of Korea; b: Research Institute of Agriculture and Life Sciences, Seoul National University, Gwanak-ro 1, Gwanak-gu, Seoul, Republic of Korea; c: Department of Bio-based Materials, Chungnam National University, 99 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea; * Corresponding author: jungoh@snu.ac.kr*

INTRODUCTION

Timber is a sustainable renewable material that has a carbon storage effect (Hafner and Schäfer 2018). As a solution to climate change, the use of timber as an alternative to steel and concrete is encouraged in mid-rise and high-rise buildings (Fleming *et al*. 2014). Fire resistance is becoming more important as timber buildings become larger and taller. The main structural support of a building is required not to collapse during an evacuation of people in the event of a fire. Generally, fire-resistance rating for two h or more is required for buildings with three or more floors. This work was planned as a preliminary study to find a way for a mass timber product to satisfy the 2-hour fire-resistance.

The development of mass timber products (cross-laminated timber (CLT) and nail laminated timber (NLT)) has made it possible to construct mid-rise and high-rise buildings. CLT is manufactured by gluing the wide faces between laminae layers. The edges of laminae within layers are not usually glued, and air gaps exist between the individual laminae (Nairn 2017). NLT is a timber product that differs from CLT. In CLT, the layers of timber are stacked crosswise in the fiber direction. However, in NLT, the wide faces of the timber lamina are placed side by side in the fiber direction and nailed (Kuhlmann and

Michelfelder 2004; Ben *et al*. 2022). NLT can be manufactured by fixing low-grade lamina with nails and can be composited with concrete to provide an economical and high-performance slab (Hong 2017). Because the laminae are fastened by nails, there are also air gaps between the laminae. The air gaps can be larger at high temperatures due to the twist or shrinkage of the laminae. Therefore, the air gaps existing between the laminae in CLT and NLT have been noted as a safety issue for fire resistance (Klippel and Schmid 2017; Ranger and Dagenais 2019).

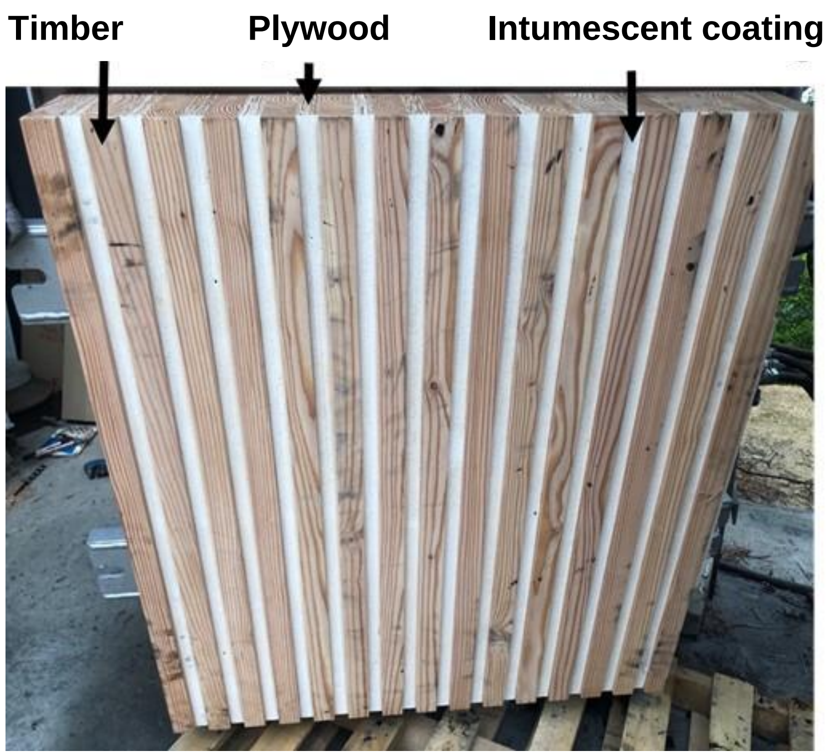
When timber is exposed to fire, the cross-section of timber can become reduced and the residual cross-section must bear the full load by itself (Schmid *et al*. 2015). The residual cross-section can be calculated using the charring rate of timber. Ranger and Dagenais (2019) investigated the charring rate of NLT depending on the air gaps. They manufactured the NLT specimens with air gaps of 1, 2, and 4 mm and tested them in the fire. The charring rate of the 4 mm gap specimen was 0.66 mm/min, which represented an increase by about 40% compared with that of the 1 mm gap specimen (0.47 mm/min). Therefore, the higher charring rate due to the gaps results in a smaller residual cross-section, and it weakens the structural performance of NLT.

One method to reduce the effects of air gaps is intumescent coating. An intumescent coating swells to 15 to 30 times its initial thickness, and the swollen layer acts as a heat transfer barrier (McNameer *et al.* 2016). The 1-h or 2-h fire-resistance paints are mainly oil-based acrylic types, and the technology focused on reducing the thickness of the coating has been developed. The intumescent coatings are commonly used for structural steel in high-rise commercial and industrial buildings to prevent fire-induced structural collapse. The effect of the intumescent coating on timber was also investigated by several researchers (Puri and Khanna 2017; Lucherini *et al*. 2019). Puri and Khanna (2017) summarized recent progress in intumescent coatings for structural timber and reviewed the chemical mechanisms of intumescent coatings. Lucherini *et al*. (2019) applied the intumescent coatings for CLT. They heated intumescent coating CLTs for 60 min at a heat flux of 50 kW.m^2. They found that the intumescent coating rapidly swelled at the start of heating, and the charring rate and temperature rise of CLT were delayed by the swelling layer. In this study, the intumescent coating was applied to nail-laminated timber to prevent the weakening of the fire resistance due to the air gaps. The effects of intumescent coating on the charring rate and internal temperature were investigated. The effects of intumescent coating thickness (1, 2, and 3 mm) were also analyzed.

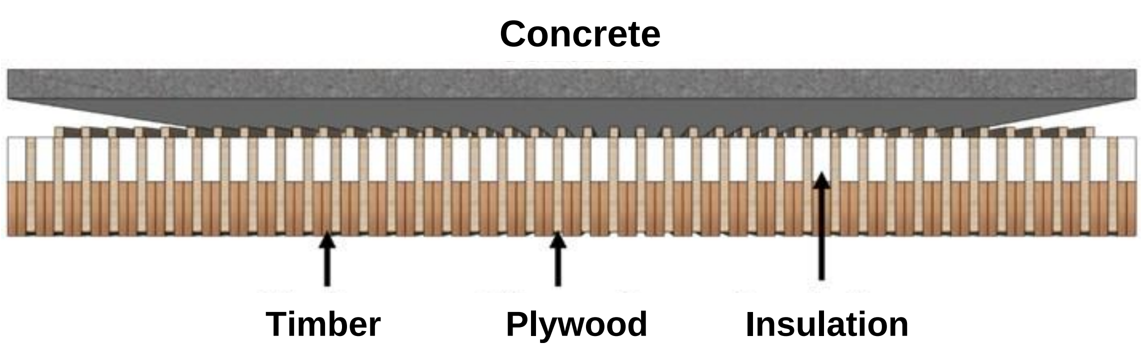
EXPERIMENTAL

Concept of Test Specimen

Figure 1 shows a manufactured fire test specimen and the NLT-concrete composite in which the test specimen was used. In the NLT-concrete composite, the timber and plywood are nailed together, and the plywood plays the role of a shear connector between timber and concrete layer (Ahn 2022). To utilize wood resources, plywood was used as a shear connector instead of steel plate and screws. However, as the charring rate of plywood (1.0 mm/min) is higher than that of timber (0.65 mm/min). According to EN 1995-1-2, the fire can easily damage the nails that mechanically connect the plywood to the timber. Applying intumescent coatings to all the bottom surfaces of a specimen is inefficient, so the intumescent coatings were only applied to the bottoms of plywood laminae (Fig. 1a).



(a) Intumescent coated specimen (bottom of specimen)



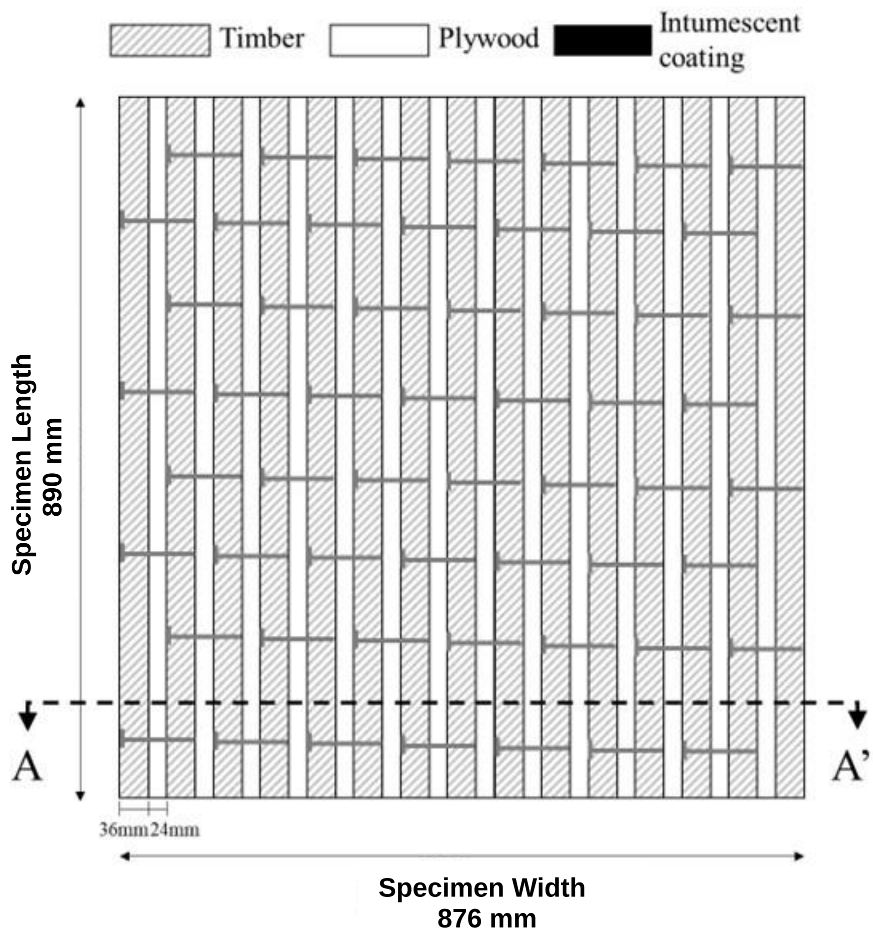
(b) NLT-concrete composite slab

Fig. 1. Test specimen and NLT-concrete composite slab in which the test specimen is used

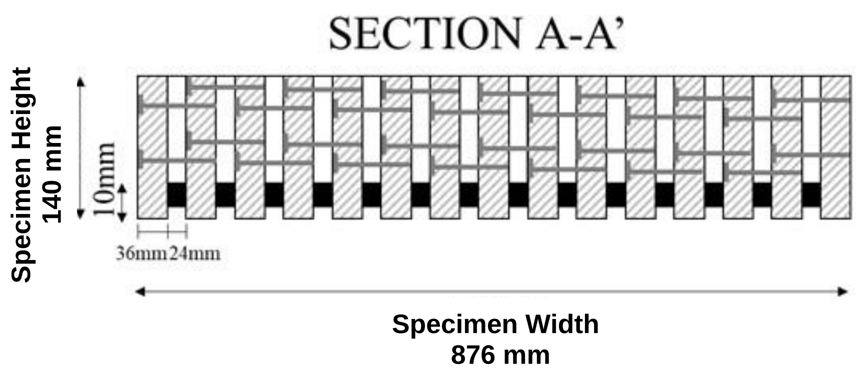
Fire Test Specimen

In the event of a fire, the bottom of the NLT slab is exposed to the fire. Thus, the timber-plywood panel was manufactured for the fire test specimen. Figure 2 shows a schematic drawing and detailed dimensions for the assembled timber-plywood panel. The panels were manufactured by alternately joining 15EA timbers and 14EA plywood laminae according to a nail-laminated timber guide (Council 2017). Both timber and plywood were made from the larch (*Larix kaempferi* Carr.) species, and the air-dry density values were 578.9 and 708.4 kg/m^3, respectively (Pang *et al*. 2020). The density of wood was calculated from the air-dry weight and air-dry volume at the test moisture content (12 ± 2%) according to BS EN 384.

The grades of the timber and plywood laminas were E10 and No. 1, respectively, according to NIFoS #2020-3 (National Institute of Forest Science 2020). The size of timber was 36 mm × 140 mm × 890 mm, and that of plywood panels was 24 mm × 130 mm × 890 mm for width × height × length. The timber and plywood laminae were fastened with nails (Simpson Strong-Tie®). The length, head diameter, and shank diameter of the nail were 75 mm, 7 mm, and 2.9 mm, respectively. The manufactured specimens were stored in the conditioning room (20 °C, 65% R.H.) for a week.



(a) Top view of specimen



(b) Cross-section of specimen
(Note: the intumescent coating layer is depicted here as thicker than the actual scale)

Fig. 2. The schematic drawing and dimensions of the assembled NLT specimen

Intumescent Coating

Table 1 shows the detailed specifications for test specimens. Four types of test specimens were manufactured of the same size (890 × 890 × 140 mm). All specimens consisted of the same timber and plywood. However, the thickness of the intumescent coating differed from 0 to 3 mm. In Fig. 2b, the actual thickness of the intumescent coating layer is illustrated as being thicker than the actual thickness because it is indistinguishable from the line in the drawing.

The commercial intumescent paint (FIREMASK SQ-2700, KCC Corporation, Wanju_Gun, Republic of Korea) was developed for steel. This is a foamable oil-based fire-resistant paint with solvent-based acrylic resin as its main component (Table 2). It can be applied to steel structures such as general buildings, factories, and industrial plants. Its recommended thickness is 3 mm for 2-h fire retardant. Steel loses approximately 50% of its load-bearing capacity at 500 °C in a fire (Puri and Khanna 2017), whereas timber does not. It must be painted several times to achieve a 3-mm thickness, and the effect of blocking the air gaps can be expected with a thickness of 1 to 2 mm. Therefore, specimens with coating thicknesses of 1, 2, and 3 mm were prepared. Figure 3 is a picture of plywood laminae coated with intumescent, before assembling the NLT specimens (Figs. 1 and 2). The intumescent coating was applied to the plywood laminae at intervals of 5 to 6 hours and the thickness of the intumescent coating layer was measured after it dried completely. After the final coat, the specimens were left at room temperature for more than 24 h to dry completely.

Table 1. Specification of Test Specimens

Test Specimen	Timber			Plywood			Thickness of Intumescent Coating[2)]		Size of Test Specimen (mm)
	Size[1)] (mm)	Number of Lamina		Size (mm)	Number of Lamina				
No.1	36×140 ×890	15		24×130 ×890	14		1 mm		876×140× 890
No.2							2 mm		
No.3							3 mm[3)]		
Control							Uncoated		

1)Width × height × length
2)The number indicates the thickness of intumescent coating after it was dried completely
3) Recommended thickness to steel structure for ensuring 2-hour fire resistance

Table 2. Main Components and Content of the Used Intumescent Paint (KCC 2022)

Chemical Name	Content (%)
Xylene	16 ~ 23
Polyphosphoric acids ammonium salts	13 ~ 20
Methacrylic acid-2-ethylhexyl acrylate-styrene polymer	10 ~ 17
Melamine	7 ~ 14
Toluene	4 ~ 11
Pentaerythritol	4 ~ 11
Titanium dioxide	4 ~ 11
Chlorinated paraffin	4 ~ 11
Ethylbenzene	1 ~ 8
Chlorite-group minerals	1 ~ 6
Solvent naphtha (petroleum), light arom.	0.1 ~ 1

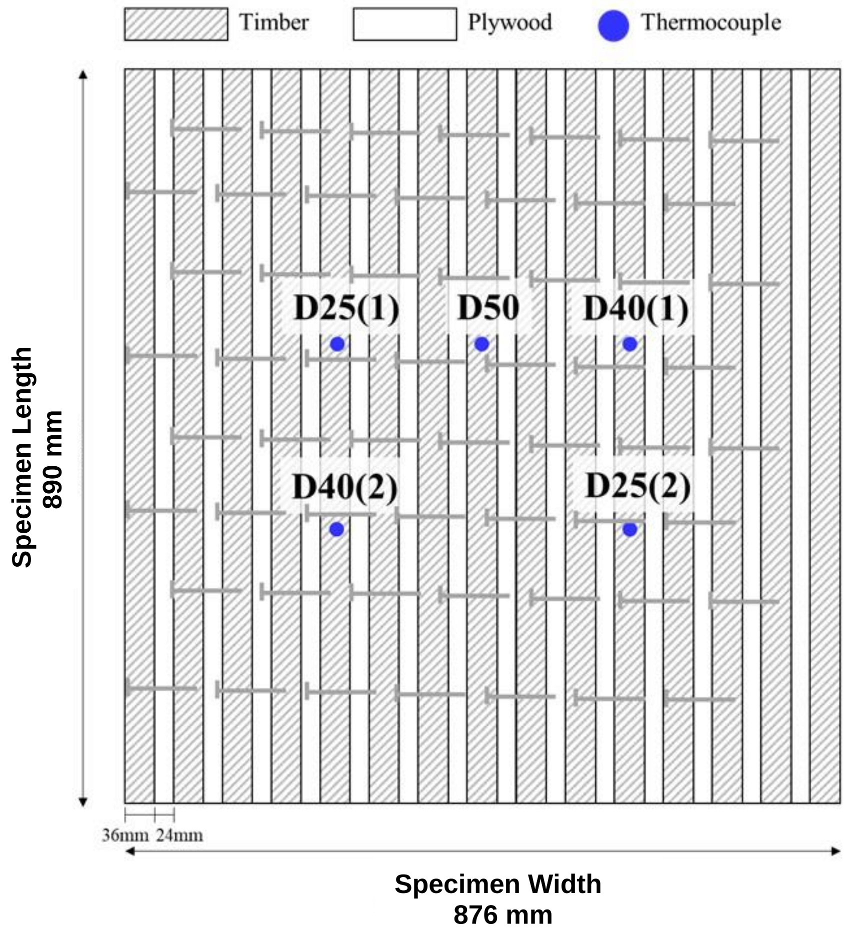
Fig. 3. Intumescent coating on plywood laminae

Thermocouple Installation

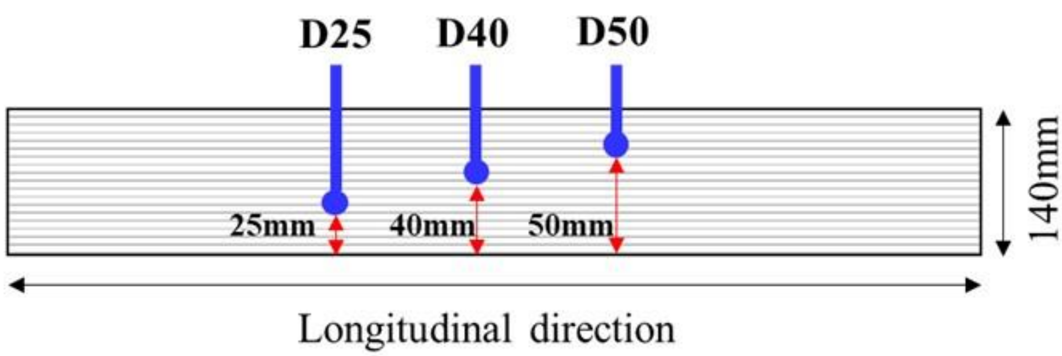
Five thermocouples were installed to measure the temperature change in each specimen. Figure 4 shows the positions and depths of installed thermocouples. All thermocouples were installed inside of the timber laminae, and each thermocouple was installed at a different depth. The depth refers to the distance of the thermocouple from the surface exposed to the fire. The temperature was measured at a depth of 25 mm, 40 mm, and 50 mm from the surface of the fire. To accurately measure the initial temperature of specimens, two sensors were installed symmetrically at the depths of 25 mm and 40 mm.

Thermocouples used in this test were TEMPSENS B-Type (Fig. 5, Tempsens Instruments Pvt. Ltd., Udaipur, India). The B-Type thermocouple has a wide measuring range (0 to 1700 ℃, accuracy: ± 5 %) and good pressure-resistant performance. Each thermocouple is sheathed with a ceramic beads insulator. Thus, it is suitable to measure a high temperature. It responds slowly for measurements below 500 ℃ and has a lower output at temperatures below 600 ℃ (TEMPSENS 2021). However, since all experiments were conducted under the same conditions, it is reasonable to check the coating effect through comparison between specimens.

When installing the thermocouples, holes were drilled from the fire-unexposed surface (opposite face to the fire), and the thermocouples were inserted in the holes. A 17 mm diameter drill bit was used in making holes, considering that the diameter of the thermocouples was 16 mm.



a) Position of the thermocouples (top view)



b) Installation depth of thermocouples (side view)

Fig. 4. Position of thermocouples installed in the specimen

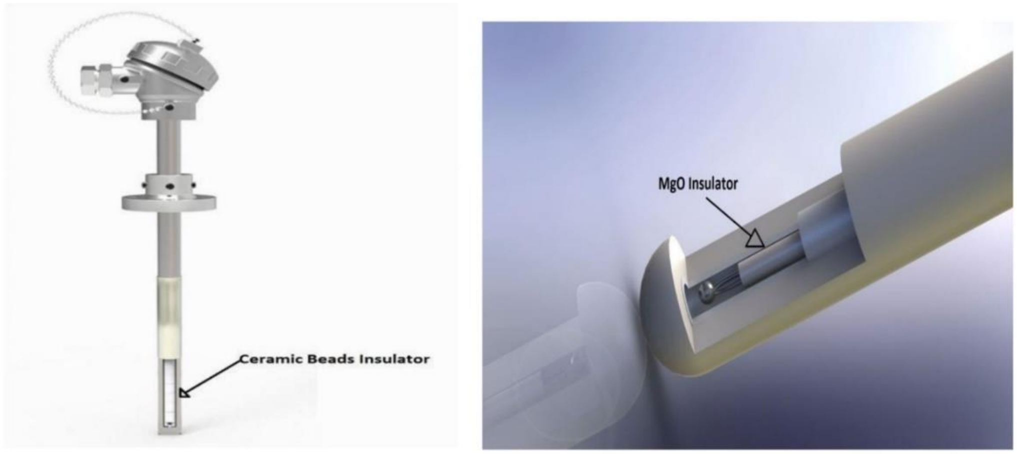


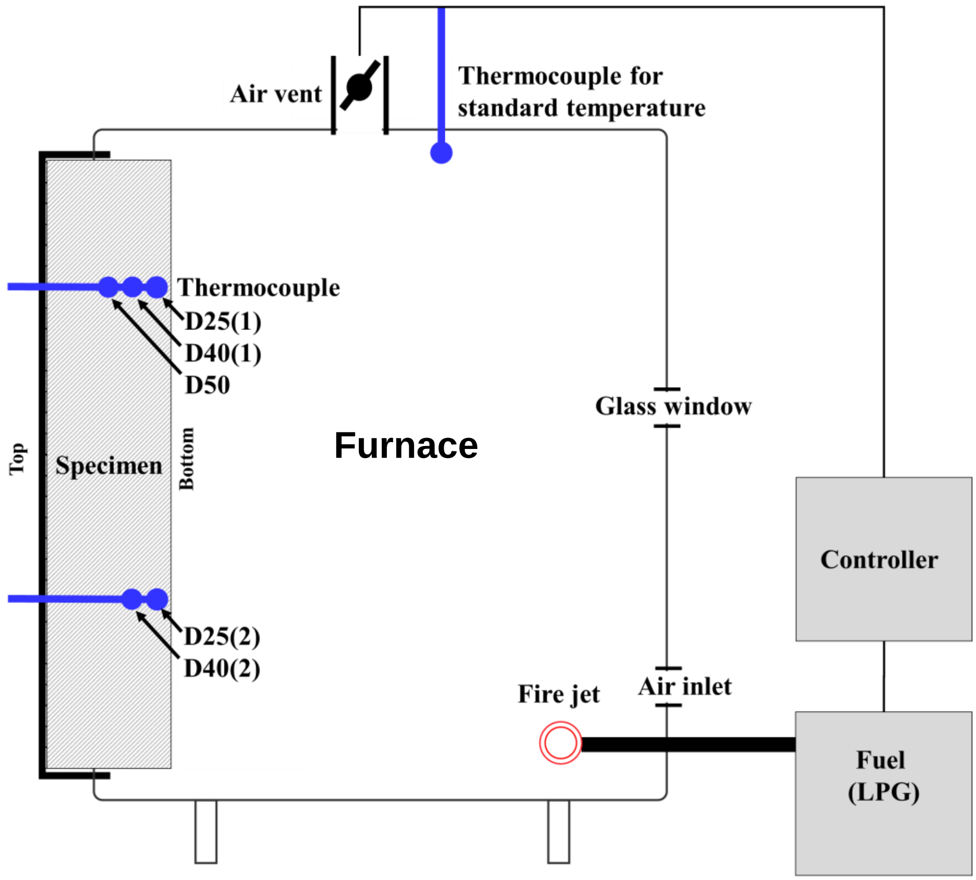
Fig. 5. B-Type thermocouple (TEMPSENS 2021)

Fire Resistance Test

Figure 6 shows the schematic system of the furnace. The furnace was designed for laboratory-scale experimentation. The temperature inside the furnace is detected by a thermocouple located at the top. Fire jet uses liquefied petroleum gas (LPG) as fuel. The gas injected into the fire jet is automatically controlled so that the internal temperature of the furnace follows the standard temperature curve of ISO 834-1.

a) Outside of the furnace

Fig. 6a. Position of thermocouples and a specimen in furnace



b) Schematic diagram of the furnace-burner system

Fig. 6b. Position of thermocouples and a specimen in furnace

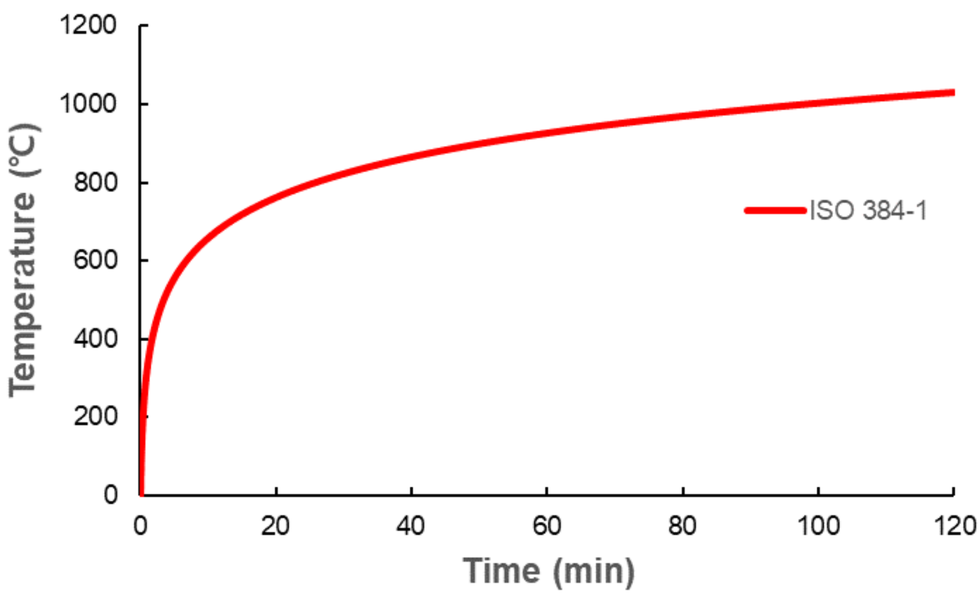


Fig. 7. Standard temperature-time curve in ISO 834-1(ISO 834-1:1999 1999)

A specimen was installed on the furnace door, and the fire was injected to char the timber-plywood panel bottom surface, as shown in Fig. 6. The fire resistance test was conducted by standing the specimen vertically, and the temperature at the top may be higher than the temperature below. However, it is sufficient to study the effect of the intumescent coating, which is the purpose of this study, and since it is installed vertically, the behavior of the intumescent coating could be observed visually through the glass window. The fire test was conducted for 2 h based on ASTM E119-20 (2020). The temperature of the furnace followed ISO 834-1 (1999) (Fig. 7). The temperature of every thermocouple was recorded once a second.

RESULTS AND DISCUSSION

Time-temperature Curve

Figure 8 shows the time-temperature curve of thermocouples at different depths in specimens. Because timber will be burning when it is above the charring temperature (approximately 300 °C (Dietenberger and Hasburgh 2016)), the temperature at the depth of specimens was analyzed based on 300 °C. The internal temperature sensor of the uncoated specimen reached 300 °C earlier than the coated specimens. The 25 mm depth reached 300 °C after 4700 seconds (Fig. 8a), the 40 mm depth after 5900 seconds (Fig. 8b), and the 50 mm depth after 6900 seconds (Fig. 8c).

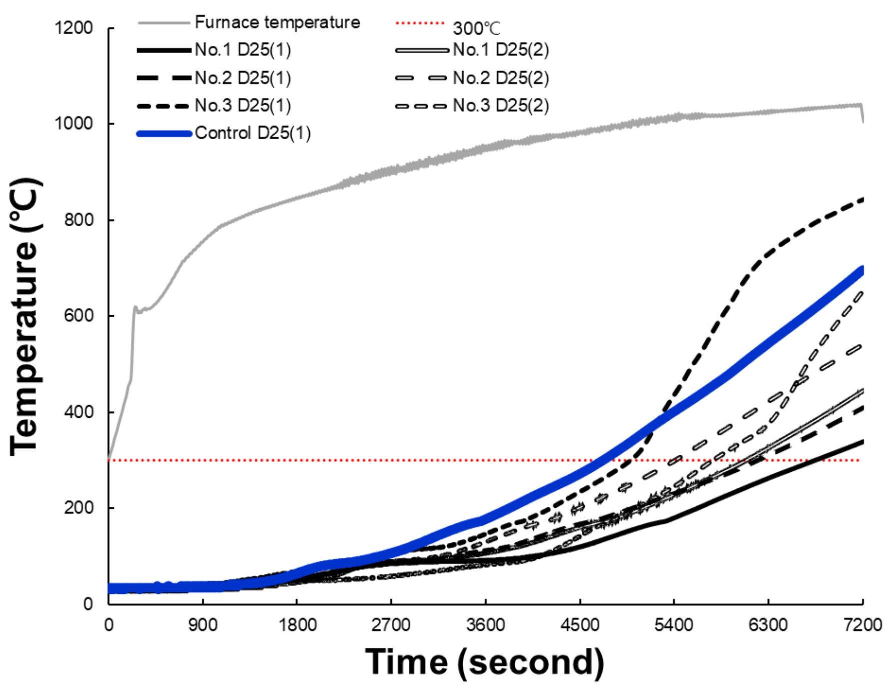
The temperature of thermocouples increased gradually during the fire test, except for D25(1) of No.3 (Fig. 8a) and D40(2) of No.1 (Fig. 8b). The temperatures of the two thermocouples rose sharply after about 5000 seconds. There are two possible reasons for the rapid temperature rise. First, the thermocouples were installed in timber laminae, which were not covered with an intumescent coating. If the plywood laminae were coated (No.1 and No.3), then the temperature rise will be determined preferentially by the condition of the timber laminae. Cracks were observed on the timber surface during the experiment (Fig. 9a). Therefore, there is a possibility that the temperature of the thermocouples could have risen rapidly due to cracks around the thermocouples. Second, it was observed that the swollen intumescent coating fell from the specimen during the experiment (Fig. 9). The falling off of the intumescent coating may have affected the temperature rise of the timber laminae.

Figure 10 shows the temperature at different depths from 60 min to 120 min after the fire test. In the uncoated specimen (Control), the temperature of all sensors exceeded 300 °C after 120 min. When the intumescent coated specimens (No.1, No.2, and No.3) were compared to the uncoated specimen, the temperature of intumescent coated specimens was clearly lower than that of the uncoated specimen. Thus, the intumescent coating caused the increase of internal temperature to be slower. This phenomenon can be explained by heat transfer as shown in Fig. 11. The figure shows the heat transfer path of the specimens during the fire test. The swollen layer of intumescent coating blocked the plywood laminae, such that the heat was preferentially transferred through the timber laminae (Fig. 11a). This effect can be expected even with a thickness of 1 mm because the coating increased by 15 to 30 times its thickness (Puri and Khanna 2017). The uncoated test specimen showed a faster temperature rise than the coated specimens because heat was transferred through the plywood and the timber laminae had three sides exposed to fire (Fig. 11b).

Figure 12 shows the times at which the temperature of each thermocouple reached up to 100, 200, and 300 ℃.

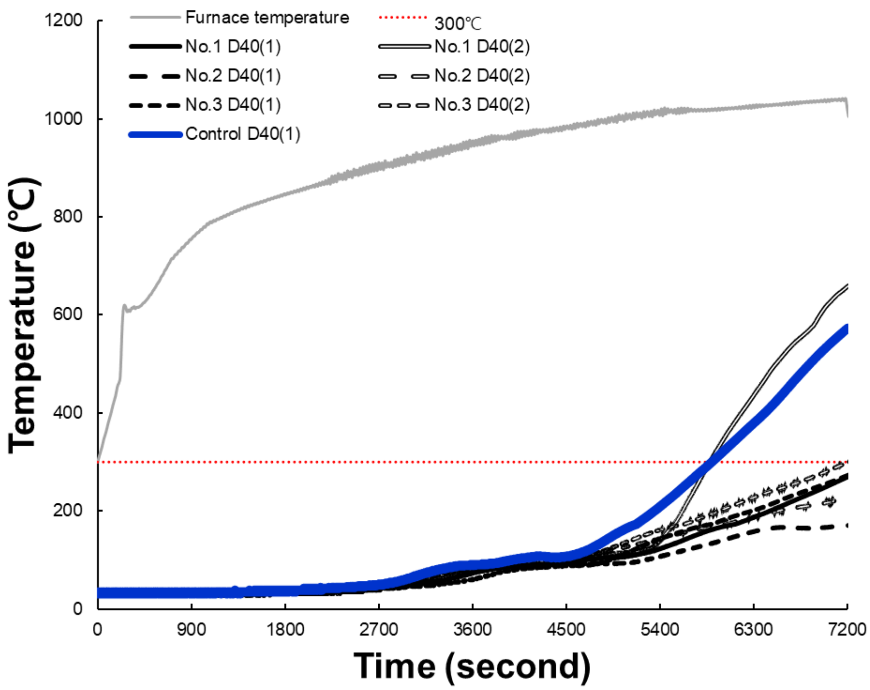
Thermocouples installed in the intumescent coated specimens took longer to reach a certain temperature than those in the uncoated specimens. This indicates that the intumescent coated specimens took more time to reach 300 ℃. As mentioned above, the intumescent coating was only applied to the plywood laminae, and the thermocouple was installed in timber laminae. Thus, the swollen layer of the coating on plywood laminae provided thermal insulation from the fire.

However, it was not observed that the delay in temperature rise increased as the coating became thicker. This indicates that heat was transferred through the uncoated timber lamina. Timber has a large density variation due to natural defects (fiber direction, knots, *etc*.). The temperature of thermocouples is affected by the condition of the timber around the thermocouples. Therefore, since the plywood was coated and the temperature rise was determined by the condition of the timber lamina, there was no difference due to the coating thickness on plywood.

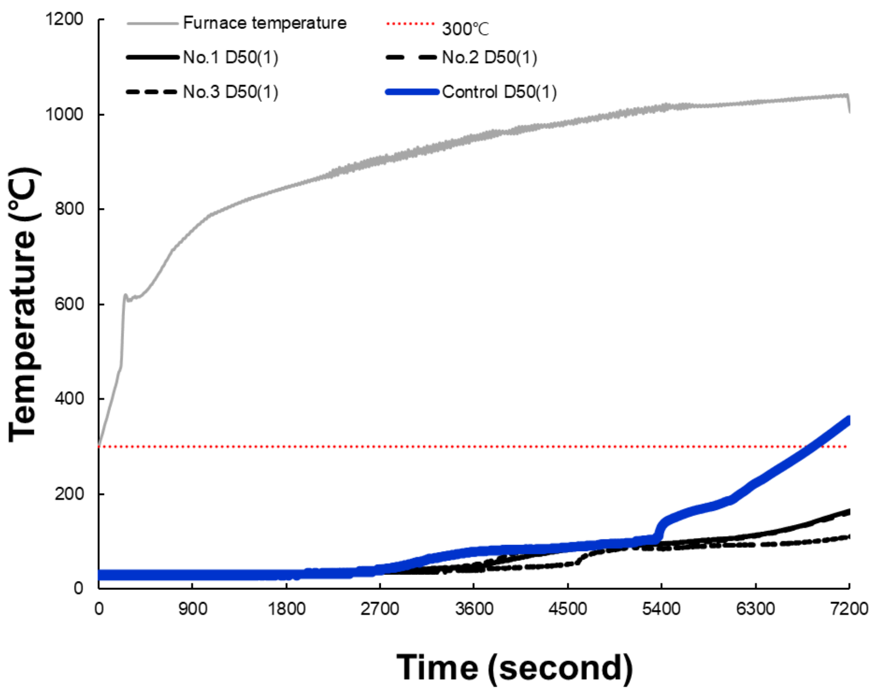


(a) D25 (25 mm depth from the fire exposed surface)

Fig. 8a. Time-temperature curve of thermocouples in specimens during the fire test

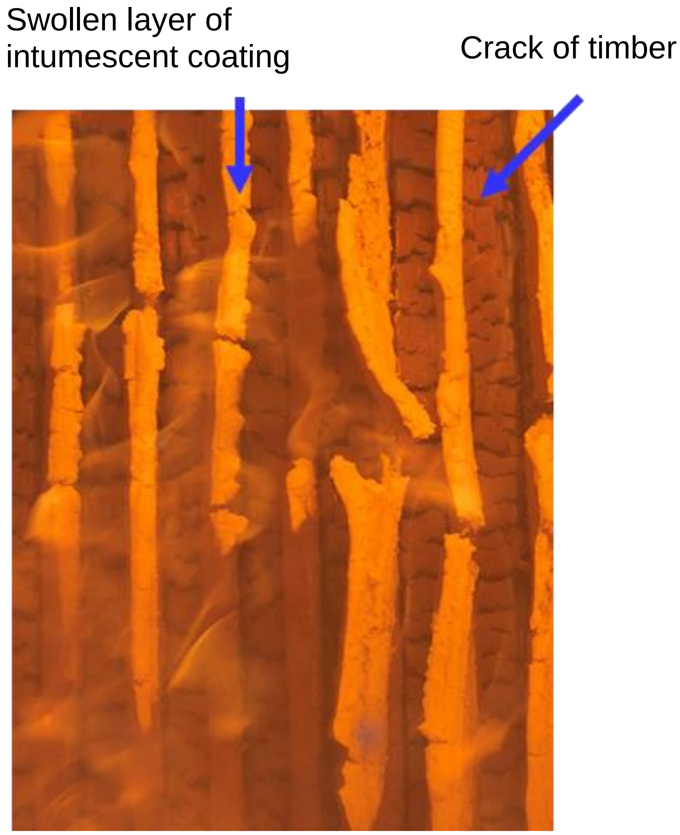


(b) D40 (40 mm depth from the fire exposed surface)

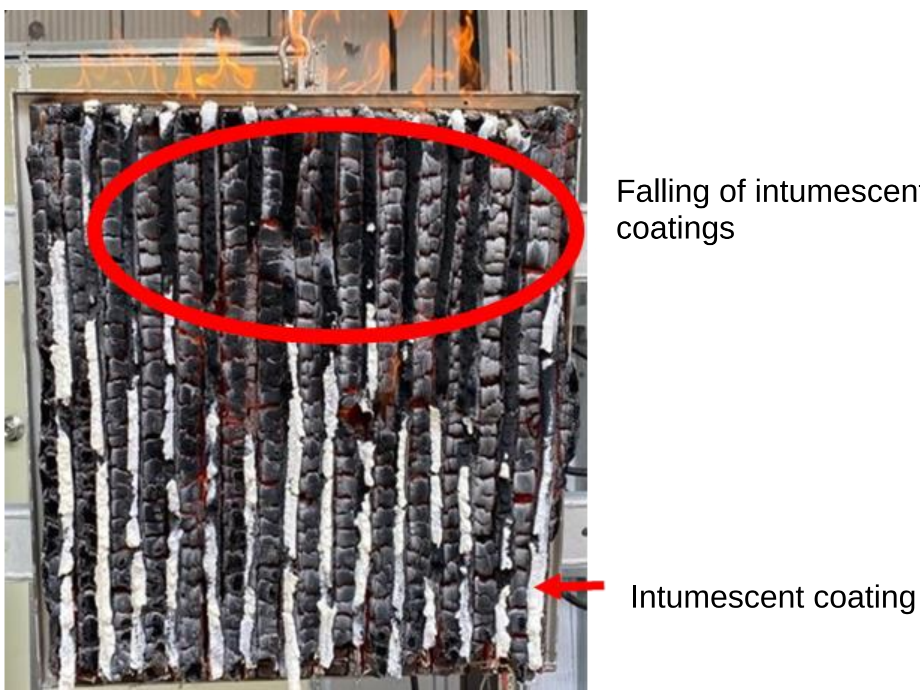


(c) D50 (50 mm depth from the fire exposed surface)

Fig. 8b,c. Time-temperature curve of thermocouples in specimens during the fire test

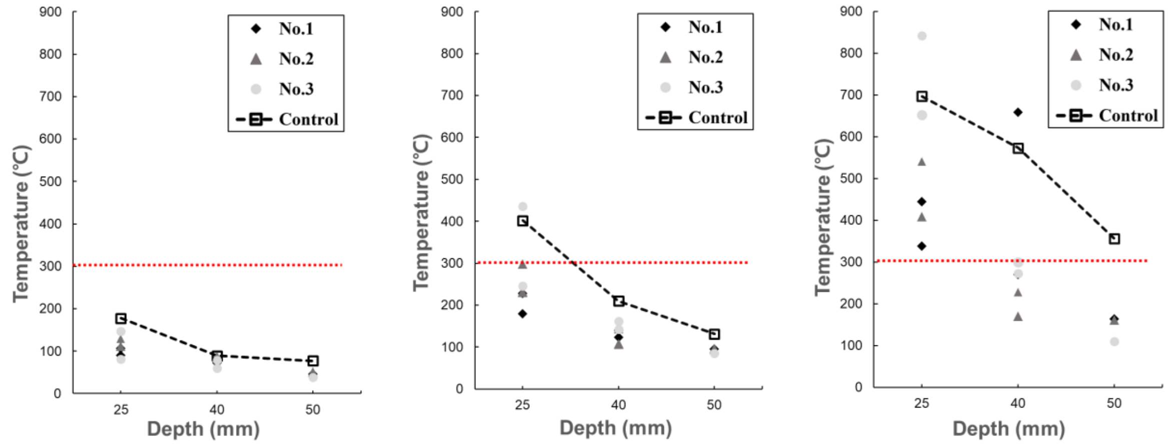


(a) During fire test



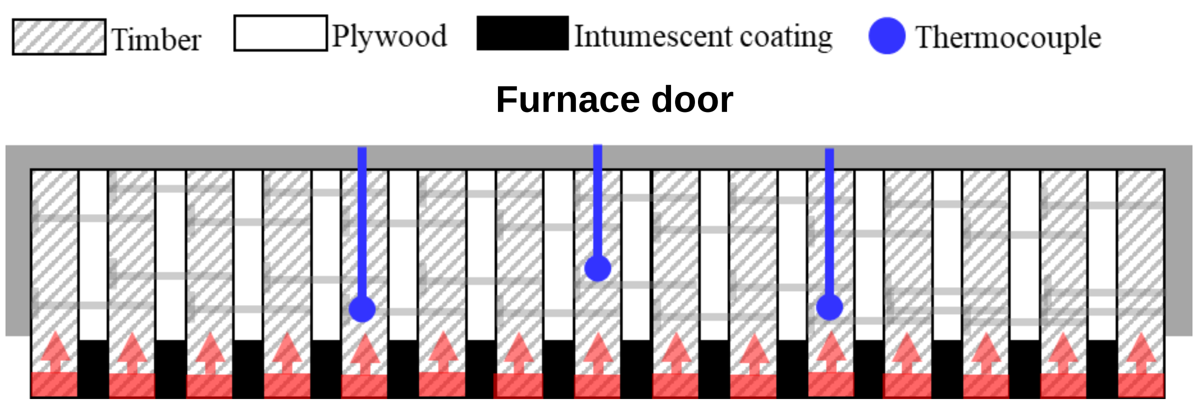
(b) After fire test

Fig. 9. Swollen layer of the intumescent coating in fire test

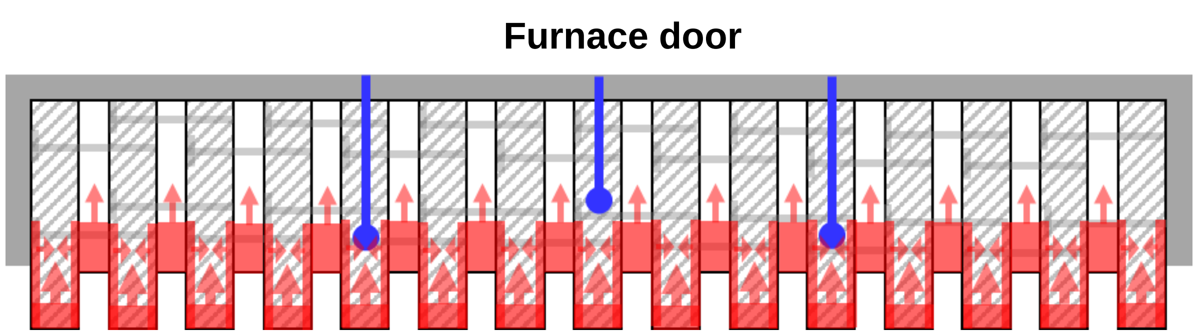


(a) 60 min **(b)** 90 min **(c)** 120 min

Fig. 10. Temperature at different depths depending on the time

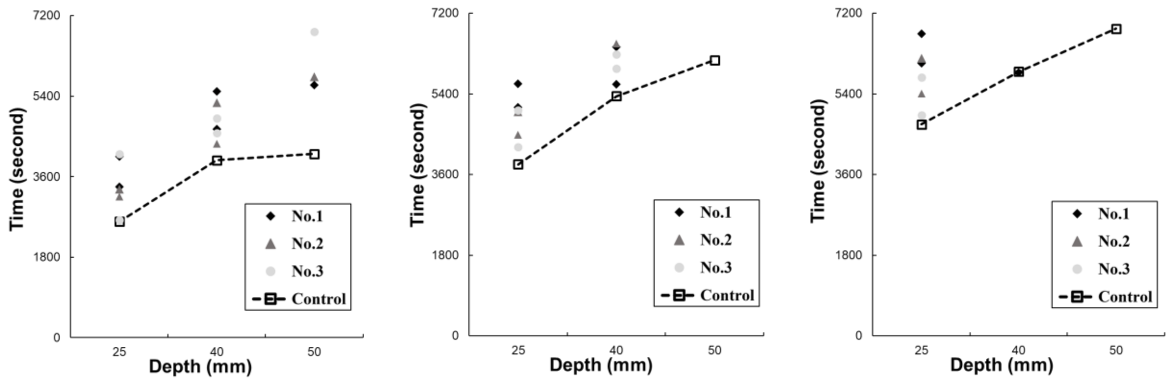


(a) One-dimensional heat transfer into timber (intumescent coated specimen)



(b) Three-dimensional heat transfer into timber (uncoated specimen)

Fig. 11. Main heat transfer path of the specimens



(a) 100 °C **(b)** 200 °C **(c)** 300 °C

Fig. 12. Time when the temperature of each location reaches 100, 200, 300 °C

Charring Rate

The char layer is considered to be a zero-strength layer (Schmid *et al*. 2015), and charring rate is the main parameter to design the fire resistance of structural timber. The charring rate is defined as the ratio between the depth of char layer formed on the timber and the fire duration (Frangi and Fontana 2003). The depth of char layer was obtained by subtracting the depth of the residual cross-section undamaged by fire from the specimen's initial depth (140 mm), as shown in Eq. 1,

$$R_t = \frac{D_{initial} - D_{residual}}{t} \tag{1}$$

where R_t is the charring rate (mm/min), $D_{initial}$ is the initial height of timber laminae (mm), $D_{residual}$ is the average of the residual depths of timber laminae (mm), and t is exposure time (min).

The residual depth of specimens was measured at the center of the specimens, as shown in Fig 13. All of the blackened parts were assumed to be a char layer to evaluate the results conservatively. After 120 min of the experiment, the door of the furnace was opened and water was sprayed on the test specimen attached to the inside of the door. The specimens were cooled naturally to room temperature, and the residual depth was measured on the second day after the experiment. Combustion of the specimen would have continued as the specimen cooled. However, the charring rate in Table 3 was calculated based on the fire exposure time (120 minutes) from a conservative point of view. The average residual depth and charring rate of each specimen are specified in Table 3. The charring rate of the intumescent coating specimens was lower than that of the uncoated specimen. The charring rate of the uncoated specimen was 0.78 mm/min, which is similar to the three-sided charring rate of that species (0.80 mm/min (EN 1995-1-2 2004)). The charring rate of the intumescent coating specimens was 0.66 to 0.68 mm/min, which is similar to the one-dimensional charring rate of that species (0.65 mm/min (EN 1995-1-2 2004)). The average charring rate of the intumescent coating specimen was reduced by 12.82% (1-mm thickness), 14.1% (2-mm thickness), and 15.38% (3-mm thickness) compared with the uncoated specimen.

Fig. 13. Measurement of the residual depth of timber laminae

Table 3. Test Results and the Required Charring Depth for Fire Design

Test Specimen	Test Results					Required Charring Depth (mm)			
	Residual depth (mm)	Charring rate[1)] (mm/min)	Ratio[2)] (%)	p-value[3)]		1 hour[4)]		2 h[5)]	
No. 1	58.77 (2.83) [6)]	0.68	87.18	0.55 [7)]		40.62	(6.39)[8)]	81.23	(12.77)
No. 2	59.71 (4.35)	0.67	85.90			40.15	(6.86)	80.29	(13.71)
No. 3	60.50 (4.48)	0.66	84.62			39.75	(7.25)	79.50	(14.50)
Control	46.00 (2.55)	0.78	100.00	1.74×10^{-6} [9)]		47.00	-	94.00	-

[1)] Calculated by Eq. 1
[2)] Ratio to the charring depth of control specimen
[3)] Analysis of Variance (ANOVA) (a significant difference (α) = 0.05)
[4)] Fire resistance for one hour
[5)] Fire resistance for two h
[6)] Standard deviation
[7)] Comparison of No.1, No.2, and No.3
[8)] Reduced charring depth compared to Control specimen
[9)] Comparison of No.1, No.2, No.3, and Control

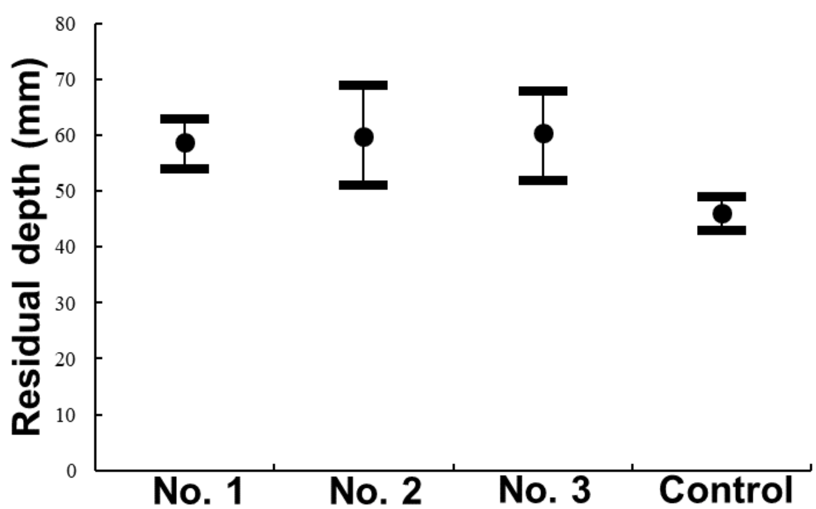


Fig. 14. Range of the residual depth of test specimens

The statistical analysis results (t-test, a significant difference (α) = 0.05) in Table 3 and the residual depth range of the specimen (Fig. 14) imply that there was no difference between 1-mm, 2-mm, and 3-mm coatings. In general, specimens are considered statistically different if the p-value is less than 0.05, (Vázquez *et al*. 2015; Gilani *et al*. 2017). The p-value between No. 1, No. 2, and No. 3 specimens was greater than 0.05. Thus, there was no significant difference in the residual depth depending on the 1-, 2-, and 3-mm coatings. However, the p-value by comparison of all specimens (including the Control specimen) was 1.74×10^{-6}, which is less than 0.05. Therefore, the uncoated specimen is considered statistically different from the coated specimens.

Fire Design of NLT with Even-laminae Intumescent Coating

The intumescent coating on plywood laminae swelled with increasing temperature in the fire test (Fig. 9). The swollen layers covered the gaps between the timber laminae. However, after about 5000 seconds, the fire on the timber spread to the plywood inside the coating, and it appeared that the coating had fallen off by gravity. This indicates the swollen layer will exhibit drop-off when a part of the cross-section area inside the coating is reduced and the coating layer becomes heavier. Therefore, a too thick layer of intumescent coating may cause a decrease in fire resistance. This is in contrast to steel, which requires sufficient insulation thickness to prevent heat transfer, because its strength rapidly decreases when it is heated to temperatures above 500 °C (Gunalan and Mahendran 2014).

In the uncoated specimen, heat passed through the plywood and exposed the timber laminae to three-sided fire exposure conditions (Fig. 11b). However, in the intumescent coated specimens, the intumescent coating covered the plywood, resulting in a delayed initial temperature rise and a slower charring rate. Since heat transfer and combustion proceed through timber laminae until the coating on the plywood falls off, the measured charring rate was similar to the one-sided charring rate of timber.

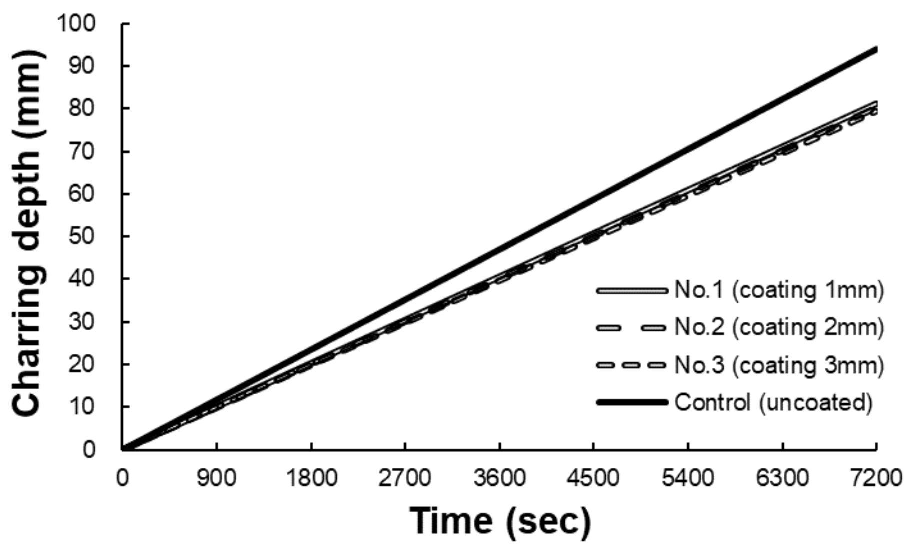


Fig. 15. Charring depth for required fire-resistance

As a result, when the even-laminae in NLT are covered with intumescent coating, the fire resistance can be designed by the one-dimensional charring condition. Figure 15 shows the designed charring depth for the required fire resistance time. The charring depth was calculated by Eq. (2) according to Eurocode (EN 1995-1-2 2004). When the NLT panel was covered with the intumescent coating, the design charring depth for two h of fire resistance was reduced by 12.0 mm (coating 1 mm), 13.2 mm (coating 2 mm), and 14.4 mm (coating 3 mm) compared to the uncoated (Table 3). Since the charring rate was obtained through a laboratory-scale furnace, this result is not related to the fire-resistance rating or the load-carrying capacity of the specimen,

$$d_{char} = \beta_i \cdot t \tag{2}$$

where d_{char} is the the charring depth for required fire resistance time (mm), β_i is the charring rate evaluated in this study (mm/min), and t is elapased time (min).

CONCLUSIONS

In this study, the effect of intumescent coating on fire resistance of NLT was investigated, and the main findings were as follows.

1. The intumescent coating on the even-laminate in NLT specimens swelled up during the fire test. The internal temperatures of all the intumescent coating specimens increased more slowly than that of the uncoated specimen. If the gap between laminae had widened, and heat had moved into the gap, then there would be no difference between the coated and uncoated specimens. This means that the swollen layer covered the gaps between laminae and prevented heat transfer into the gap as well as plywood during the fire test.
2. All of the residual cross-sections for the intumescent coating specimens were larger than the uncoated specimen, and all of the charring rates were slower than the uncoated specimen. The statistical analysis (ANOVA) showed there was no significant difference between 1-mm, 2-mm, and 3-mm coatings. Thus, even as little as 1-mm thickness of the intumescent coating was sufficiently effective in the delay of initial temperature and reducing charring rate.
3. Since the coating on plywood prevented the combustion of the plywood, the combustion of the wide surfaces of timber laminae between the plywood was also prevented. Thus, the charring depth of the coated specimens can be designed with the one-dimensional charring condition. When the charring depth of the coated specimens was calculated by Eurocode with the measured charring rate, the design charring depth for two hours was reduced by 12.0 mm (coating 1 mm), 13.2 mm (coating 2 mm), and 14.4 mm (coating 3 mm) compared to the uncoated.

ACKNOWLEDGMENTS

This study was conducted with the support of the ‘R&D Program for Forest Science Technology (Project No. 2020224A00-2222-AC02)’ provided by the Korea Forest Service (Korea Forestry Promotion Institute).

Availability of Data and Materials

Not applicable

Competing Interests

The authors declare they have no competing interest.

Authors' Contributions

Sung-Jun Pang analyzed the test results and wrote this manuscript. Kyung-Sun Ahn and Min-Jeong Kim analyzed test data and designed figures and tables. Sung-Wook Hwang designed the specimens and revised this manuscript. Seog Goo Kang designed an experimental test procedure and operated the test facility. Hyo Won Kwak and Hwanmyeong Yeo designed this research and fire test. Jung-Kwon Oh managed this research project and approved the final manuscript.

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Article submitted: June 22, 2022; Peer review completed: July 20, 2022; Revised version received: August 26, 2022; Accepted: August 27, 2022; Published: September 8, 2022.
DOI: 10.15376/biores.17.4.5999-6018