

Title: Experimental Research on Moisture Transfer, Burning and Charring Behavior of Glue Laminated Larch Under Fire Heating Using Cone Calorimeter

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Experimental Research on Moisture Transfer, Burning and Charring Behavior of Glue Laminated Larch under Fire Heating using Cone Calorimeter

Abstract

Cone calorimeter tests were conducted to investigate the moisture transfer, burning and charring behavior of timber under fire heating. 99 x 99 x 50mm glue laminated larch specimens were made in cross grain and straight grain directions. The initial surface moisture contents were 15.1 wt. % (cross grain specimens) and 13.5 wt.% (straight grain specimens). Twenty specimens were heated at 50 kW/m² of irradiance. Heating duration was varied between 10 to 50 minutes. Internal temperatures, surface temperature, heat release rate, and water contents were measured during heating. Charred depth, colored depth and burnt-out depth was measured after cooling. Heat release rate was measured by oxygen consumption method. Temperature was measured by an IR camera and thermocouples. Moisture content was measured by the electrical resistance method. Charring and coloring temperatures were estimated by using the measured charred or colored depth data and temperature histories. Burnt-out depth, charred depth and colored depth were slightly larger in case of straight grain specimens than that in cross grain specimens. Heat release rates were almost constant after reaching the first peak values. Temperature creep was observed in each location at about 100 °C, according to evaporation of water. Maximum internal temperature of each specimen at each location increased while heating duration increased. Peak value of moisture content varied by each specimen, but the temperatures corresponding with peak moisture content were almost the same, i.e., around 100 to 120 °C. Moving speed of moisture peak is about 1.30 mm/min. Charring and coloring temperature were about 380 and 260 °C, respectively.

Keywords: Radiant heating; Glue Laminated Larch; Temperature creep; Moisture content; Heat release rate; Charring temperature.

1 Introduction

As the wood is a sustainable and environmentally friendly material, it has been widely used in construction in many countries. However, wood will be decomposed into char and combustible gas by pyrolysis when exposed to high temperatures. The progress of pyrolysis of timber material will result in failure of structure. In addition, once the pyrolysis gas will be ignited, heat generated by the combustion of pyrolysis gas will cause further pyrolysis, making the reaction self-sustaining. Special attentions must be paid to flammability when using timber materials to buildings.

Many researches on fire safety of timber materials were reported in the past. Terrei *et al.* [1] conducted a heating experiment using cone calorimeter to investigate the critical heat flux of ignition of spruce wood. They have found that ignition only occurs when heating intensity is above 45 kW/m². For lower heat flux, ignition is not observed but smoldering combustion takes place. Li *et al.*[2] used medium density fiber board as specimen and found that the mass loss rate of the specimen is linear to heating intensity. Chatani *et al.*[3] studied the rate of char oxidation during glowing and smoldering combustion.

They found that the critical heating intensity for continuation of char oxidation is above 8.4 kW/m². The corresponding surface temperature was 286 °C. As to large scale tests, for example, Niwa *et al.*[4] conducted large scale furnace tests of laminated veneer lumber (LVL) columns and beams under ISO834 heating. Lennon *et al.* [5] conducted large scale fire tests to investigate the burning behavior of various timber floor system, using a compartment with internal dimension of 4m x 3m. Suzuki *et al.*[6] conducted loaded and non-loaded full-scale fire resistant test of timber panels and walls to investigate the burning behavior of timber panel, and to develop a simple method for estimating the fire resistance of timber panels. Xu *et al.*[7] investigated the fire resistance of timber floor assemblies exposed to ISO 834 standard fire heating protected by different fire protection. However, although so many research were conducted to investigate the fire safety of timber materials, there are still some topics to be investigated.

The first topic is about moisture transfer inside timber material under fire heating. Most of the experimental research have focused on the heat transfer process (temperature, HRR, etc.). However, the moisture transfer process, should also be considered. Although there are many research reported on direct measurement of wood moisture contents in normal temperature (like Brischke *et al.* [8], Baranski *et al.*[9], Otten *et al.*[10], Hwang *et al.*[11], Hafsa *et al.*[12], Schiere *et al.*[13], etc.), research on in situ measurements of moisture contents inside wood under fire heating over time (like what have done by Kimura *et al.*[14], White *et al.* [15], etc.) is rare.

One of the reasons for investigating moisture transfer inside timber material is that moisture content influences many kinds of physical properties, such as mechanical properties. A literature review by Gerhards[16] shows that the shear modulus decreases by 20 % while bending strength decreases by 25 % when moisture content increases from 12 % to 20 %. Similar results were also found by other researchers [17] [18]. For moisture contents inside timber element, internal liquid moisture transfer occurs by temperature gradient, moisture content gradient and pressure gradient[19][20]. Moisture content will change with time and position due to phase change and mass transfer of water. Non-uniform moisture distribution will be developed inside timber material under fire heating. This leads to difference of physical properties in different location, which complicates the behavior of timber elements in fire.

The second topic is about charring temperature. Since wood and char have different thermal properties, it is important to identify the temperature of wood pyrolyze into char while conducting numerical simulation of timber material under fire heating. Also, calculation results of charring depth can be derived by using calculated temperature history, which broaden the applicable range of calculation results. However, the charring temperature of wood is unclear. According to a review by Frangi *et al.*[21], temperature of charring front measured by different researchers varies in a range of 253~360 °C, which is too wide to use in simulation. Other charring temperature, like 260 °C[6] and 300 °C[22], were also used. A precise charring temperature is needed.

The target of this research is to analyze the moisture transfer, burning factor and charring behavior of glue laminated larch under fire heating. For that purpose, cone calorimeter[23] was used to heat timber specimen with high intensity for 10 to 50 minutes. Heat release rate from surface, internal temperature, moisture content, charred depth, burnt-out depth and colored depth were measured.

2 Materials and Methods

2.1 Experimental Setup

The experiments were conducted using a cone calorimeter. **Figure 1** shows the experimental setup. Each specimen was exposed to radiation with intensity of 50 kW/m² for 10 to 50 minutes. A spark igniter was placed between the specimen and the cone heater to ignite the combustible gas generated by the pyrolysis of the specimen. The spark igniter was removed after the combustible gas was ignited. Heat release rate was measured by oxygen consumption method. After the heating period, specimen was placed on ceramic fiber wool for cooling down to room temperature.

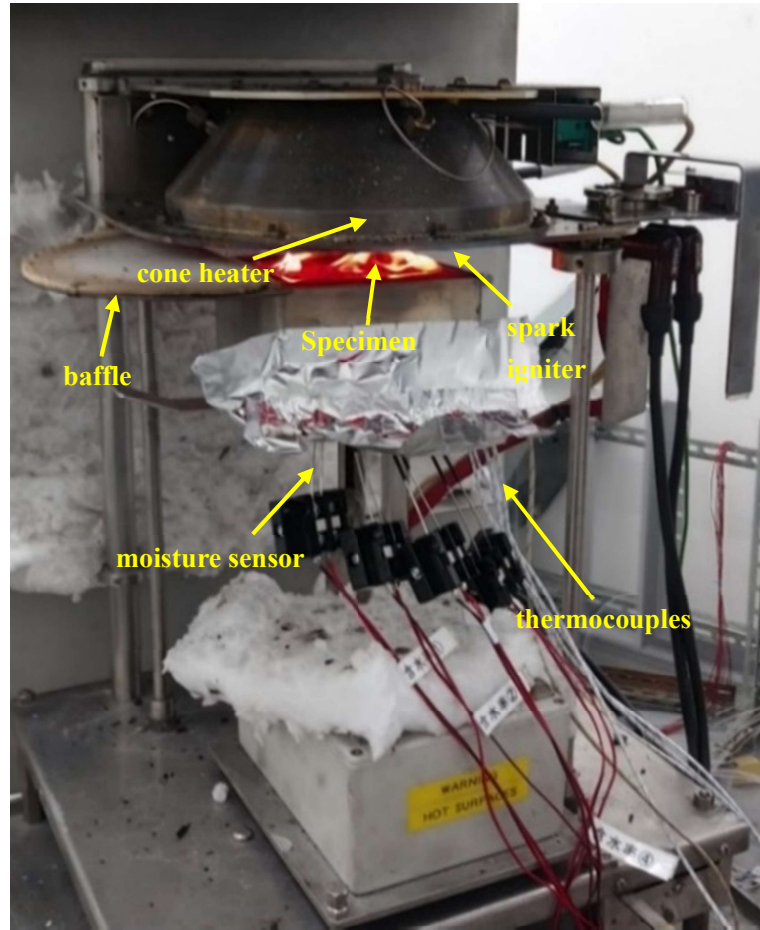


Figure 1: Experimental setup

2.2 Specimens

Specimens used in this work were laminated larch wood with 99 x 99 mm in size and 50 mm thickness. 20 specimens were used in total, 10 of cross grains specimens and 10 of straight grain specimens. Laminar thickness was about 25 mm. Experiments was named in the format of “Specimen type(C/S)-heating time-experiment number”. For example, C-10-1 means the cross-grain specimen (C) for 10 minutes heating, first run. **Figure 2** illustrates examples of straight grain and cross grain specimens used in this experiment. The cross grain specimens were created so that the cross-grain surface is heated from top. Straight grain specimens were created so that the cutting edge is heated from top. Red arrows in **Figure 2** represents the direction of heating. In creating straight grain specimens, it was difficult to unify the direction of annual ring, thus the cross and straight grain laminas were partially mixed.

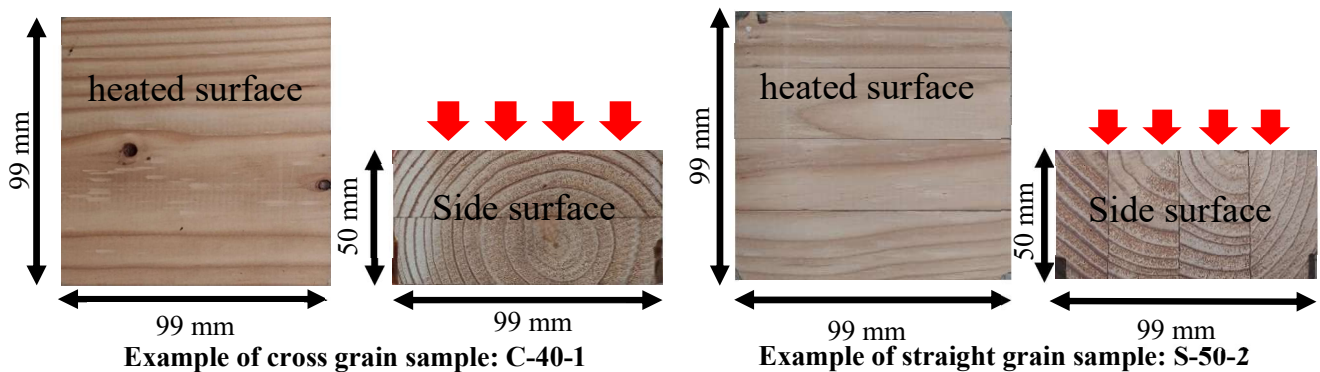


Figure 2: photographs of specimens

Side surfaces of the specimen were sealed by aluminum foil tape to reduce the inflow of oxygen. Note that aluminum foil tape was broken in experiments C-40-2 and C-50-1. These experiments were thought to be in failure and an additional experiment C-40-3 was conducted. Summary of experimental conditions is shown in **Table 1**.

Table 1 Summary of experimental conditions

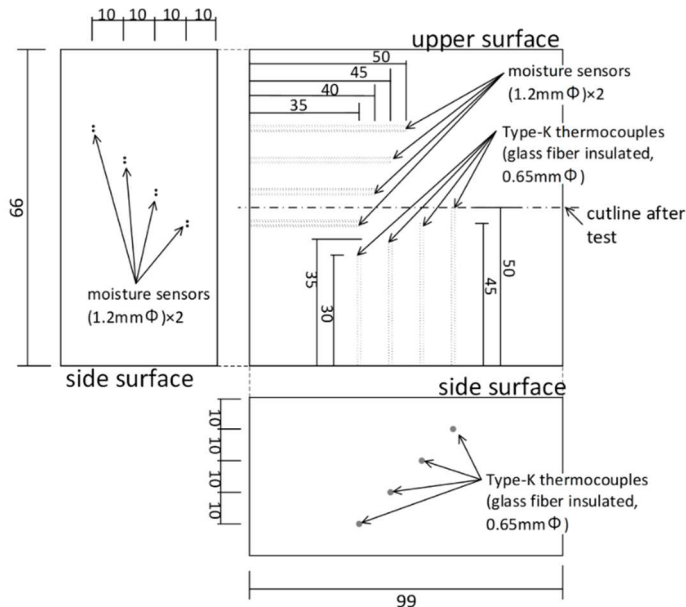
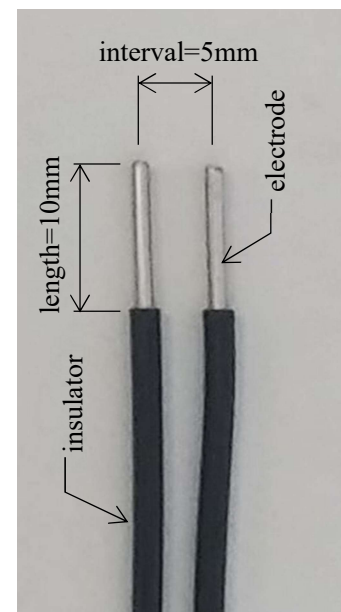
Type/Time	10min	20min	30min	40min	50min
Cross grain(C)	C-10-1	C-20-1	C-30-1	C-40-1	(C-50-1)
	C-10-2	C-20-2	C-30-2	(C-40-2)	
				C-40-3	
Straight grain(S)	S-10-1	S-20-1	S-30-1	S-40-1	S-50-1
	S-10-2	S-20-2	S-30-2	S-40-2	S-50-2

Specimens were cured in a room with constant temperature (23 °C) and relative humidity (50 %) for one month. Air dry density of cross grain specimens (C) are 565 ± 16.8 (average value $\pm$ unbiased standard deviation) kg/m^3 , while density of straight grain specimens(S) is 531 ± 18.3 kg/m^3 . Average thermal conductivity, measured by transient hot wire method[24] is 0.221 W/m.K for cross grain samples and 0.177 W/m.K for straight grain samples. Density of specimens was measured via 10 specimens created and cured in same condition, while thermal conductivity was measured via 3 specimens. Initial moisture contents of each specimen were measured by non-destructive high frequency wood moisture meter. Initial moisture contents (air dry) were 15.1 ± 1.6 wt.% for cross grain specimens(C), 13.5 ± 2.7 wt.% for straight grain specimens.

2.3 Measurement of temperature and moisture contents

The arrangement of temperature and moisture sensors are shown in **Figure 3(a)**. Unit of length in **Figure 3(a)** is mm. Type K thermocouples (0.65mm diameter, response time 2 seconds) were placed at 10 to 50mm at every 10mm from heated surface. The temperature was measured at every 10 seconds. Surface temperature of specimen was measured by an infrared camera at every one second.

It is desirable to measure the moisture content inside timber material continuously and non-destructively during heating. Many non-destructive moisture contents measurement technique was developed in the past, including the NMR technique, γ -ray attenuation technique, electrical resistance method, etc. [25][26]. Special equipment is needed to use contactless measurement method by NMR technique or by γ -ray technique [26], which is difficult to apply to high temperature conditions. Therefore, moisture content was measured based on electrical resistance method in this work. Pairs of stainless-steel electrodes were inserted inside specimen with 5mm interval and 10mm length. Moisture sensor used in this experiment shown in **Figure 3(b)**. The electrical resistance between electrodes was measured by insulation resistance testers (Kyoritsu KEW 3551, 0.01 M Ω – 4,199 M Ω) and/or by a data logger (Eto Denki, CADAC-3, 0 – 650 k Ω). The electrodes were set at 10 - 40mm from heating surface at every 10mm. Electrical resistance was measured at every 30 seconds. In each measurement, resistance data was recorded after 5 seconds since the start of each measurement to ensure the stability of data.

**(a) Arrangement of sensors****(b) Stainless steel moisture sensor****Figure 3: Images about temperature and moisture sensors**

2.4 Calibration equation between moisture content and electrical resistance

A calibration equation was needed to convert measured electrical resistance from moisture contents. The relation between gravimetric moisture contents W and electrical resistance r can be written in the form of equation (1)[27].

$$\ln r = -b \ln W + a \quad (1)$$

Where W is the gravimetric moisture content [kg/kg], r is the electrical resistance [MΩ], a and b are parameters. According to equation (1), parameters a and b can be calculated by the slope and intercept of regression line of $\ln r$ versus $\ln W$ plot. Relation of moisture content and electrical resistance of Western Larch measured by James at 300 K (26.7 °C) [28] was used to calculate the parameters a and b . The electrical resistance in James' data was measured by using electrodes with 31.75 mm spacing.

The regression plot is shown in **Figure 4**. Since equation (1) actually describe a power relation between r and W , the relation between gravimetric moisture content and electrical resistance at normal temperature can be written as equation (2) by using slope and intercept determined by the regression.

$$\ln r = -8.667 \ln W - 12.714 \quad \rightarrow \quad r = \exp(-8.667 \ln W - 12.714) \quad (2)$$

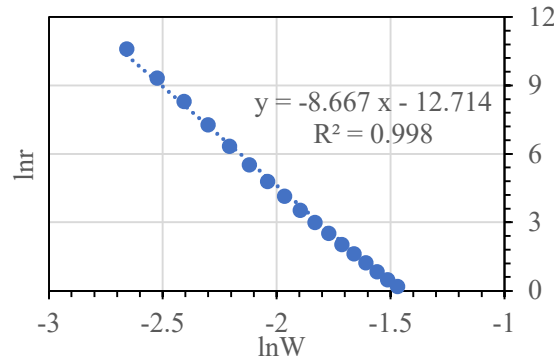


Figure 4: The regression plot of $\ln W - \ln R$, using data measured by James[28]

For temperature dependence, it is mentioned by Vermaas[27] that the specific volumetric electrical conductivity changes with temperature following Arrhenius type exponential function, as shown in equation(3).

$$c = \theta e^{-\frac{E}{RT}} \quad (3)$$

Where c is the specific volumetric electrical conductivity [MΩ⁻¹m⁻¹], E is the activation energy [J/mol], R is the universal gas constant [8.314 J/(mol·K)], T is the temperature [K], θ is a constant. Since conductivity is the reciprocal of resistance and since electrical resistance can be calculated using length data and specific electrical resistance, temperature dependence of electrical resistance can be calculated by equation (4).

$$r = \theta' e^{\frac{E}{RT}} \quad (4)$$

Where r is the specific volume conductivity [MΩ] and θ' is a constant. By substitute resistance at reference temperature T_0 and a temperature T and express $r(T)$ with $r(T_0)$, the temperature dependence of resistance can be described in equation (5).

$$r(T) = r(T_0) e^{\frac{E}{R}(\frac{1}{T} - \frac{1}{T_0})} = e^{\frac{E}{R}(\frac{1}{T} - \frac{1}{T_0})} e^{-12.714} W^{-8.667} \quad (5)$$

According to Davidson, activation energy varies with moisture content and tree species, and can be described by exponential functions of moisture content W ([29], referenced from [27]). However, the inverse function of equation (5) will be difficult to solve analytically if E expressed by a function of W . Thus, the average of 4 activation energy values obtained by different workers of different types of wood, summarized by Vermaas[30], were used here. The activation energy at 24 % moisture content was $E=4.33 \times 10^4$ J/mol. The activation energy at 24 % moisture content is about 60~70 % of activation energy at 12 % moisture content, which means that the constant approximation will not introduce large errors. Inverse function of equation (5) can be used to calculate the moisture content using electrical resistance data measured.

Since the distance and length of electrodes in this work and James' experiment[28] are different, the measured resistance data should be corrected. Assuming the specific resistance of the samples in this work and James' measurement[28] is the same, the following equation can be derived using relation between specific resistance and electrical resistance.

$$r_1 = \frac{A_2/l_2}{A_1/l_1} r_2 \quad (6)$$

where r is the electrical resistance(M Ω), A is the area of resistor(mm²), l is the length of resistor(mm). Subscripts 1 and 2 correspond with resistance data by James and that in this work respectively.

The flow of electrical current between two electrodes is shown in **Figure 5**. The cross sectional shape of area for current flow is like a circle. By assuming that the radius of circle is proportional to the interval of electrodes, the total area of current flow is shown in **Figure 5(c)**. The cross sectional area of current flow, which is equal to the area of resistor A expressed in equation (6), can be expressed by equation (7).

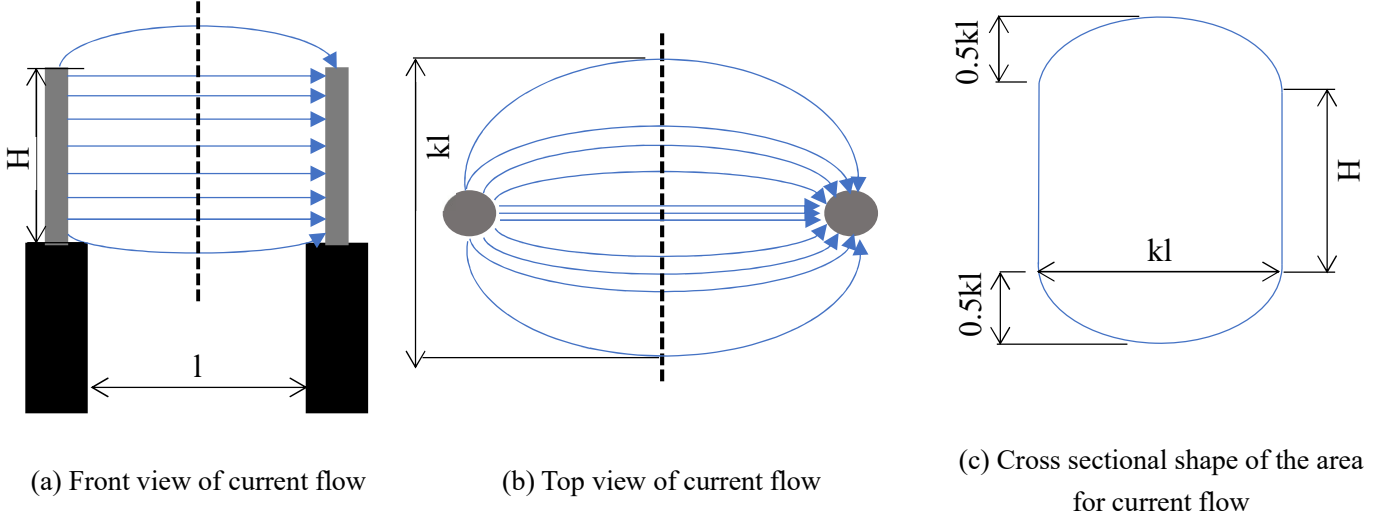


Figure 5: Electric current flow between two electrodes

$$A = kHl + \frac{\pi}{4} k^2 l^2 \quad (7)$$

where H is the electrode length [mm] and l is the interval of two electrodes[mm]. A/l can be expressed by equation (8).

$$\frac{A}{l} = kH + \frac{\pi}{4} k^2 l \quad (8)$$

Current flow is mainly crossed near the electrodes. For those areas far from electrode, there are basically no current passing these areas. The constant k was set to 0.5 to express this phenomenon.

The interval of electrodes, l , is 5mm in this work, and 31.75 mm (1.25 inch) in James' experiments. As for the length of electrodes, H is 10mm in this work and 7.9375 mm (0.3125 inch) in James' work. By substituting these values to equation (8), the ratio of A/l can be expressed in equation (9) and (10).

$$\frac{A_1}{l_1} = kH_1 + \frac{\pi}{4} k^2 l_1 = 0.25 \times 7.9375 + \frac{\pi}{4} \times 0.25 \times 0.25 \times 31.75 = 3.543 \quad (9)$$

$$\frac{A_2}{l_2} = kH_2 + \frac{\pi}{4} k^2 l_2 = 0.25 \times 10 + \frac{\pi}{4} \times 0.25 \times 0.25 \times 5 = 2.745 \quad (10)$$

By using these values, it is possible to obtain the correlation factor $(A_2/l_2)/(A_1/l_1)$ as $2.745/3.543 = 0.775$.

Inverting equation (5), the relation between W and r can be expressed by equation (11). Since the equation (5) was derived from James' data, the symbol r_1 was used here, instead of $r(T)$.

$$W = \left(\frac{r_1}{e^{\frac{E}{R}(\frac{1}{T} - \frac{1}{T_0})} e^{-12.714}} \right)^{-\frac{1}{8.667}} \quad (11)$$

Substituting equations (5), (9) and (10) to equation (11), moisture content W can be calculated by electrical resistance measured in this work r_2 [M Ω] and local temperature T [K] by equation (12).

$$W = \left(\frac{0.775r_2}{e^{\frac{E}{R}(\frac{1}{T} - \frac{1}{T_0})} e^{-12.714}} \right)^{-0.115} = \left(\frac{e^{\frac{E}{RT_0}} e^{12.714} 0.775r_2 e^{\frac{-E}{RT}}}{e^{\frac{E}{R}(\frac{1}{T} - \frac{1}{T_0})} e^{-12.714}} \right)^{-0.115} = \left(8.921 \times 10^{12} r_2 e^{\frac{-E}{RT}} \right)^{-0.115} \quad (12)$$

where E/R is approximately equal to 5207.

3 Results and Discussion

3.1 Burning Behavior

3.1.1 Ignition time, ignition temperature and heat release rate

Surface temperature measured by infrared camera at 0~60 seconds were presented in **Figure 6**. Ignition time and ignition temperature were identified based on the occurrence of sharp temperature rise. The average ignition time and temperature of cross grain specimens(C) were 23.9 ± 6.0 s (average value $\pm$ unbiased standard deviation) and 360 ± 13.9 °C, respectively. For straight grain specimens, the results were 15.7 ± 3.8 s and 340 ± 31.3 °C, respectively. The average value of ignition time and ignition temperature for cross grain specimens are higher than straight grain specimens. This is because of the difference of thermal inertia of wood in different direction.

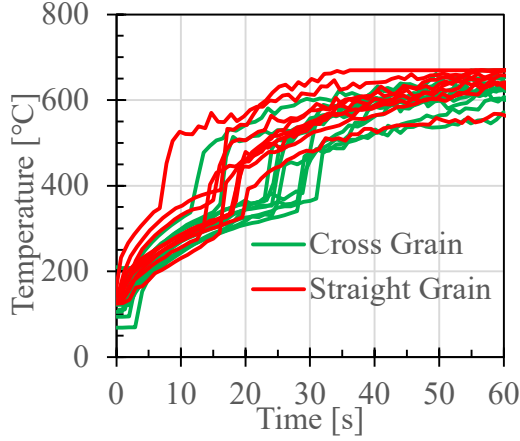


Figure 6: Surface temperature

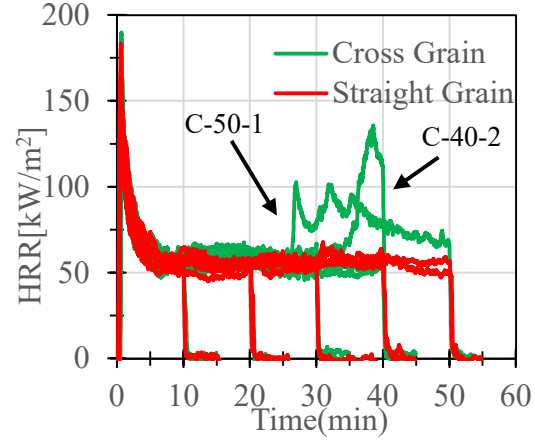


Figure 7: Heat release rate

The effective thermal inertia of specimens can be estimated by using equation of ignition time[31]. According to Quintiere[32], for thermally thick solids, the ignition time t_{ig} [s] at small times can be expressed by following equation while neglecting the heat loss from the surface.

$$t_{ig} = \frac{\pi}{4} k \rho c \left(\frac{T_{ig} - T_{\infty}}{q} \right)^2 \quad (13)$$

where t_{ig} is the ignition time [s], T_{∞} is the surrounding temperature [°C], and q is the heat flux incident on surface[kW/m²]. Converting this equation, the effective thermal inertia I can be calculated by equation (14):

$$I = \sqrt{k \rho c} = \frac{q}{T_{ig} - T_{\infty}} \sqrt{\frac{4 t_{ig}}{\pi}} \quad (14)$$

By substituting the surrounding temperature, ignition time and ignition temperature into the equation (14), the effective thermal inertia of cross grain samples are 816.86 ± 102.45 J/(m²·°C·s^{1/2}), while for straight grain samples, this value is 712.55 ± 122.98 J/(m²·°C·s^{1/2}). Although the variation is wide and about 15 % of the value, it is obvious that the effective thermal inertia in cross grain samples is higher than straight grain samples.

Thermal inertia is determined by the product of thermal conductivity, heat capacity and density. Since the heat capacity of wood is independent to its direction of grain, and both the local density and thermal conductivity of cross grain specimen is higher than straight grain specimen, it can be also estimated that thermal inertia in cross grain samples is higher.

Measured heat release rate is shown in **Figure 7**. The heat release rate of all the experiments increased rapidly after ignition. After reaching a peak value of about 150 kW/m², heat release rate decreased to about 50 kW/m² within 5 minutes and kept constant afterwards. Heat release rate at steady states in all the experiments are similar but heat release rates in cross grain specimens are slightly larger than straight grain specimens. In the experiments C-40-2 and C-50-1, heat release rate increased after reaching the steady period. This was caused by the failure of aluminum foil insulation on the side surfaces. Fresh air might have entered the specimen from the side surface and initiated the burning from the rear side.

3.1.2 Internal temperature

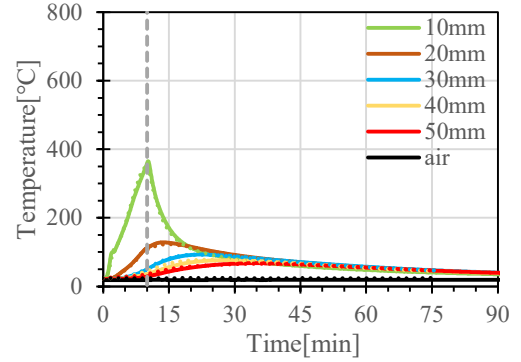
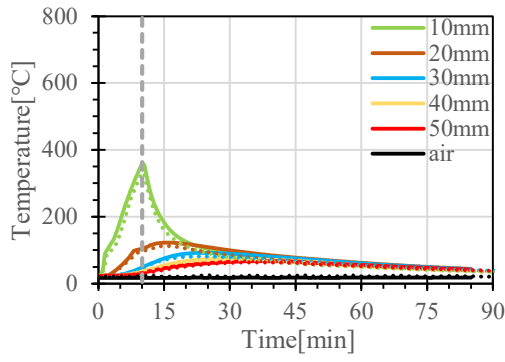
Figure 8 shows the internal temperature measured by the thermocouples. Solid lines mean data measured in the first run and dashed lines mean data measured in the second run. In case of experiments C-40, the second run was in failure. Thus, the dashed line represents the result in the third experiment, C-40-3.

Heating Time

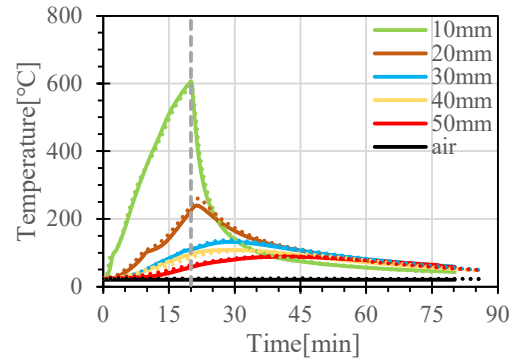
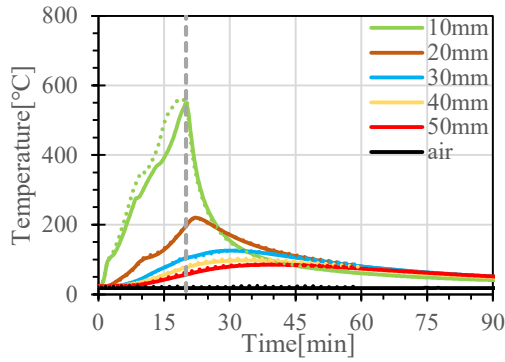
cross grain specimens (C)

Straight grain specimens (S)

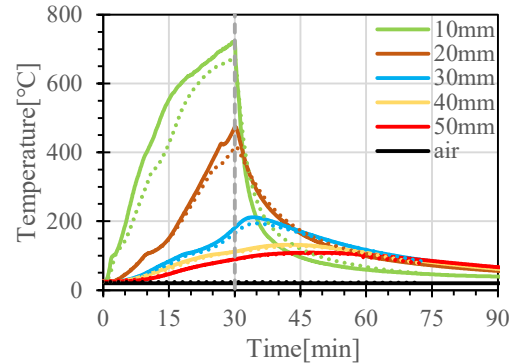
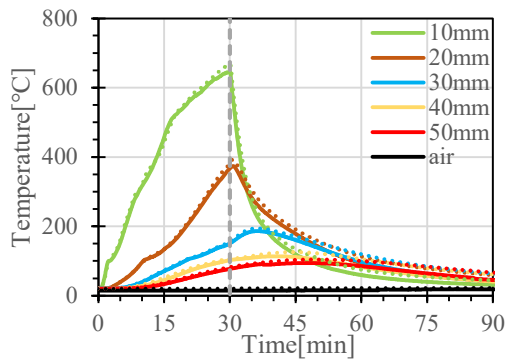
10min



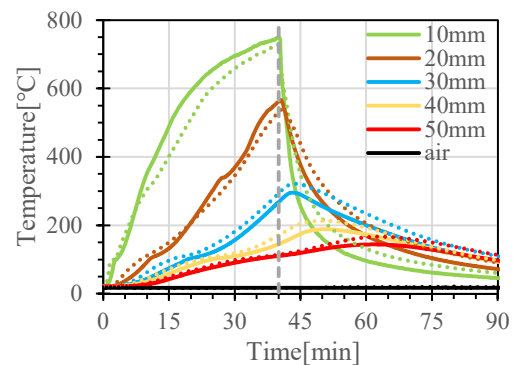
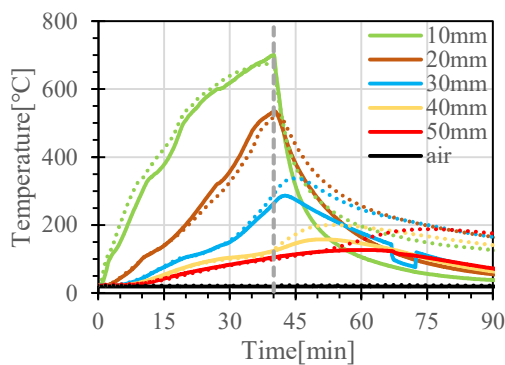
20min



30min



40min



50min

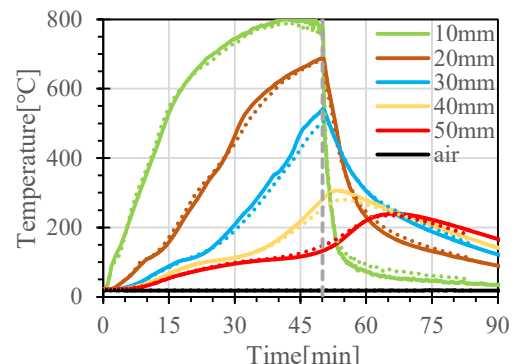
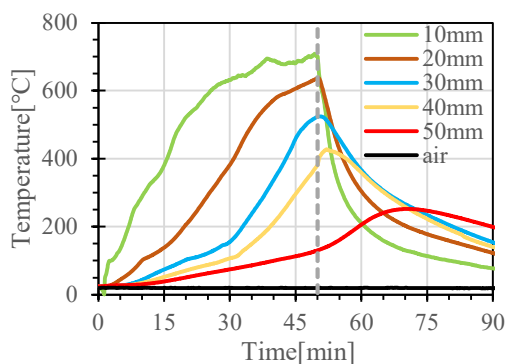


Figure 8: Internal temperature measured by thermocouple on each condition

The temperature creep was observed at each location at about 100 °C at almost all the locations in all experiments. This is caused by the heat generation by adsorption of water vapor first, then followed by desorption of water. The period of temperature creep increased as the distance from heating surface increased. Since the creep period approximately represent the time of water evaporation, increase of creep period was thought according to following reasons. One reason is the difference in inflow heat flux. Locations near the heated surface receive larger heat flow than inside locations. Secondary, according to moisture transfer inside wood conduit driven by pressure, moisture and temperature gradients, moisture content inside was increased from initial value. Lower heat flux and high moisture content finally leads to increase in time of evaporation of water inside.

Wood pyrolysis is also an endothermic process. However, the temperature creep did not exist near the pyrolysis temperature. The reason why this phenomenon occurs is that pyrolysis gas combustion happens after the gas was released from surface. The combustion of pyrolysis gas is an exothermic process with large heat of reaction, and the sum of reaction heat of wood pyrolysis and gas combustion is positive.

Temperature at locations near the heating surface started to decrease quickly after heating. For location near rear surface, temperatures continued to rise after heating stopped since the heat was conducted from the locations of near heated surface. Temperature at each location converge to a close value at about 50~60 minutes after heating stopped, besides temperature at 10 mm location (or 20 mm location in experiment with 40 minutes or 50 minutes of heating time). This is because of the shrinkage and crack formation in charring layer. Thermocouples installed on these locations contacted with air due to shrinkage and crack formation in char layer, which leads to convective heat exchange during cooling period.

Internal temperature of straight grain specimens is slightly higher than cross grain specimens. Combustion is easier to occur in the directions tangential to annual rings according to the difference of local density, which corresponds with lower thermal inertia.

3.2 Charring Behavior

3.2.1 Specimen after heating

After heating, specimens were cut vertically in the direction of fiber. **Figure 9** shows the vertically cut sections. Charring depth increased gradually as heating time increased. 3~4 deep cracks were observed in all samples, with the crack interval at different samples are similar. Crack depth is almost equal to charring depth. At samples C-40-2 and C-50-1, oxygen flew in from sides and burning combustion occurred at side surfaces.

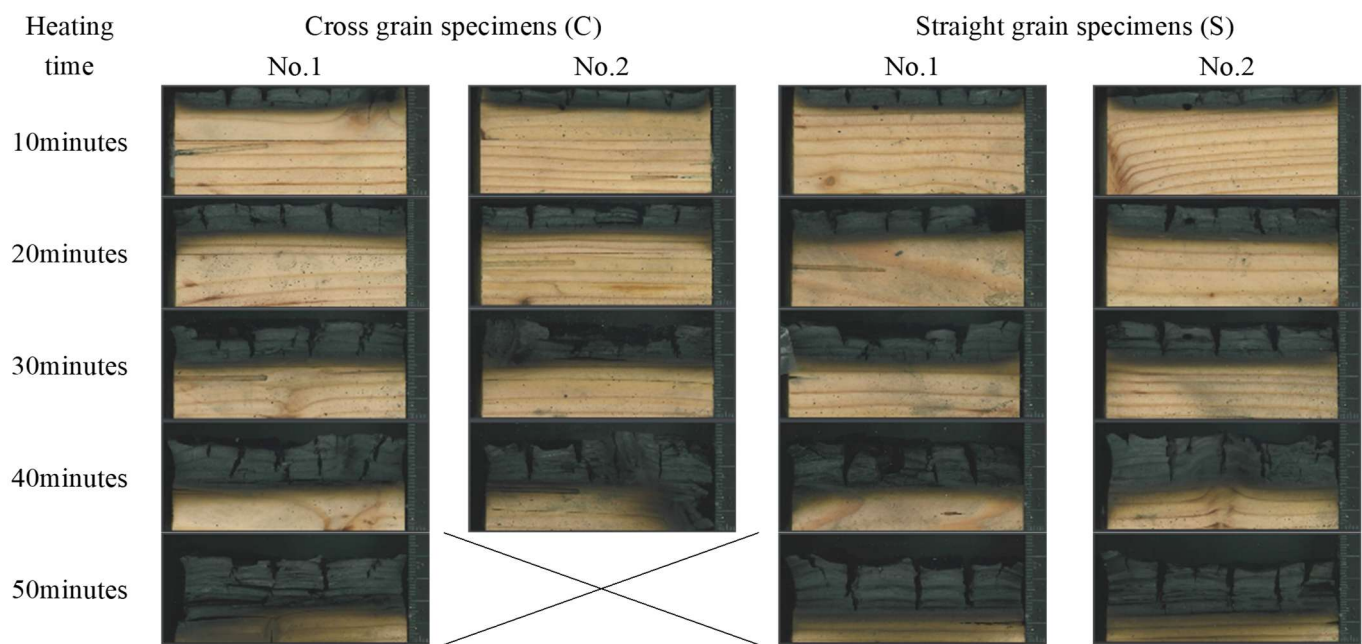


Figure 9: Section of specimen after heating

Colored front, charred front, and burnt-out front were determined by visual confirmation while brittle charred front was determined by both visual and contact confirmation. Colored front was defined as the location where color of wood started

to change from that of virgin wood, while the wood is still hard and not completely charred. Charred front was defined as the location where the wood was charred. Brittle charred front was defined as the location where the charring layer is brittle, porous, and easy to carve marks. Burnt out front was defined as the top surface of the specimen after the experiment. Colored depth, charred depth, brittle charred depth, and burnt-out depth were defined by subtracting the distance between the fronts and non-heated rear surface from the original thickness as shown in equation (15).

$$L = 50 - \Delta L_{front,rear} \quad (15)$$

where L is four types of depths, $\Delta L_{front,rear}$ is the length from four types of fronts to non-heated rear surface. L and $\Delta L_{front,rear}$ are in the unit of mm. Measurement were conducted by using tape measurements with 1 mm accuracy. Measurement was conducted twice at different location for each specimen. An example of located colored front (yellow line), charred front (gray line), and burnt-out front (red line) is shown in **Figure 10**. Brittle charred front was not shown here, since it is hard to determine only by visual information.



Figure 10: Example of location of colored, charred, brittle charred and burnt-out front (S-30-2)

Measured data of four types of depth were presented in **Figure 11**. The charred depth at 50 min of heating was about 33 mm for cross grain and 36 mm for straight grain. The charring rate was about 0.72~0.76 mm/min, which is similar to the results obtained in previous large-scale tests[6]. Colored depth was about 12 mm in case of 10 minutes of heating, while the color was completely changed in case of 50 minutes heating. Coloring rate was about 0.98~1.00 mm/min. Burnt-out depth was about 1/3~1/4 of charred depth. Charred depth, brittle charred depth and burnt-out depth changed almost linearly with heating duration in both specimens. In comparison, the colored depth, charred depth and burnt-out depth is slightly larger in straight grain samples.

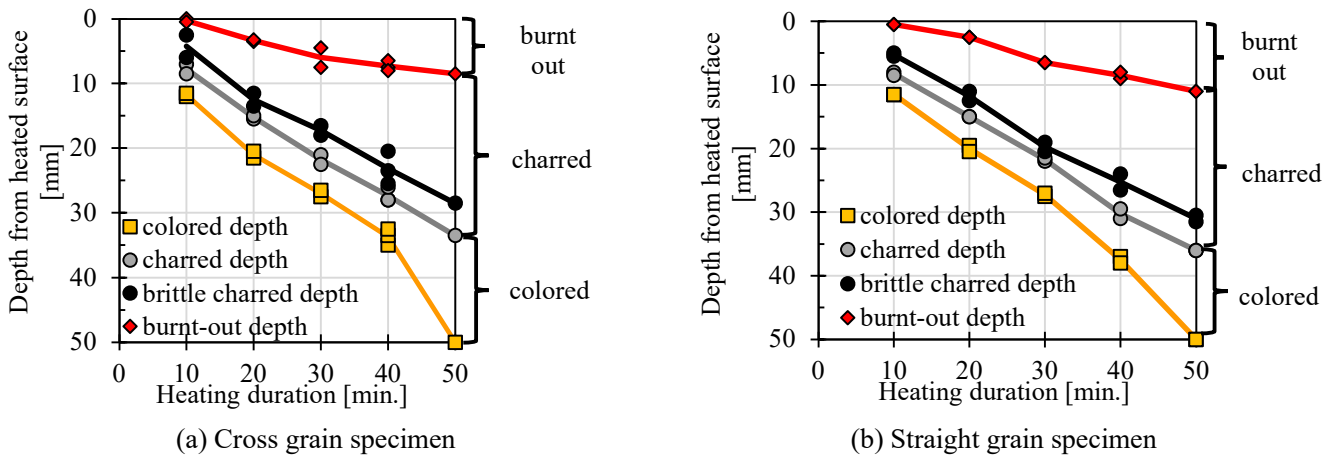


Figure 11: Colored depth, charring depth and burnt-out depth from heating surface

3.2.2 Charring and Coloring Temperature

Charring and coloring temperatures were estimated based on temperature history and observation of charred and colored depths. To explain the estimation method, an example of C-30-1 is shown in **Figure 12**. Following the measured internal temperature history, the maximum temperatures at each location are plotted in **Figure 12(b)** against the depth from heated surface. Using the results in **Figure 11**, charred and colored depth are plotted on **Figure 12(b)** by vertical lines. By reading the temperatures at the crossing points, temperature at charring and coloring front were obtained. Since the maximum temperatures gradually decrease in the direction from heated surface to rear surface, temperature of charring front and coloring

front were thought to be the charring and coloring temperatures. As for the example shown in **Figure 12**, charring and coloring temperatures were 355 °C and 234 °C, respectively.

Charring and coloring temperatures of all the other experiments were calculated in the same way. The results are shown in **Figure 13**. For cross grain specimens, the charring temperature was about 336~491 °C, coloring temperature is in the range of 206~312°C. Average value for charring and coloring temperature is 381 °C and 254 °C, respectively. For straight grain specimens, the average charring and coloring temperature is 381 °C and 263 °C, respectively. Coloring and charring temperatures on cross grain and straight grain specimens is similar. The charring temperature estimated in this work(about 380 °C) is much higher than charring temperature reported by Schaffer[33](referenced from[21]), as 288 °C, which is widely used as the charring temperature[34].

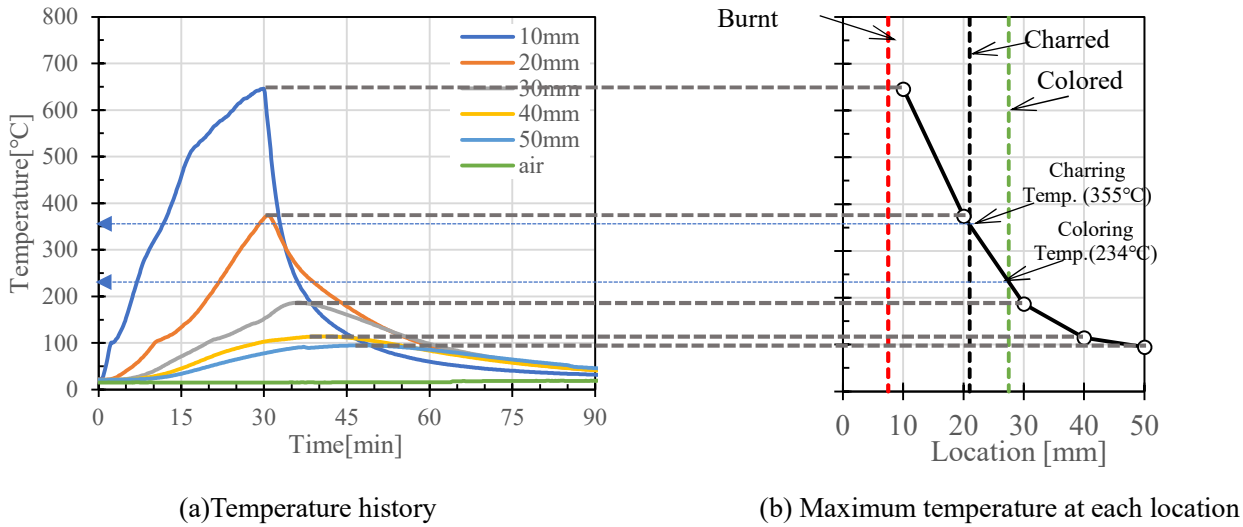


Figure 12: Temperature history of C-30-1

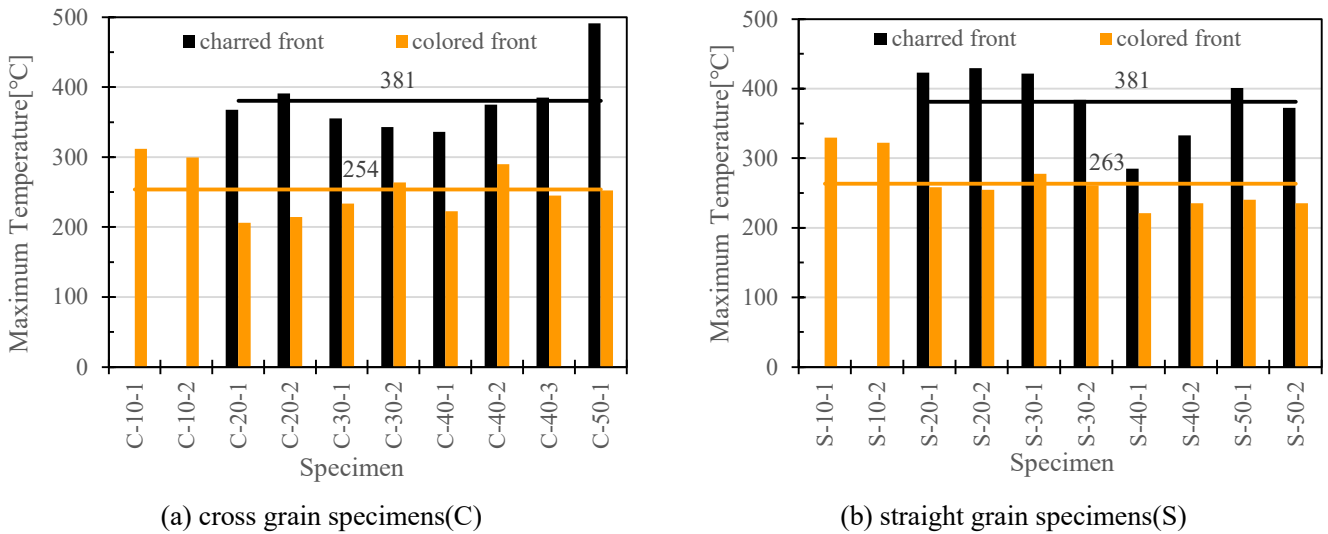


Figure 13: Charred and Colored temperature measured by highest temperature history

According to the results of thermogravimetric analysis (TGA) of larch by Sun *et.al*[35], mass loss starts at about 200°C and becomes significant at about 240~260°C. Mass loss rate reached to its maximum value at about 340~360°C and become slow and steady at about 380°C. Since the mass loss is caused only by wood pyrolysis in the temperature range of about 200~380°C, the rate of pyrolysis is equal to the mass loss rate. It is possible to compare these temperatures to temperature values measured in cone calorimeter (CCM) experiment. Coloring front represents the location that pyrolysis starts, so the coloring temperature should correspond with the temperature of pyrolysis start. Average values measured in CCM experiments (254°C and 263°C) are approximately in the range of 240~260°C. Charred front represents location that pyrolysis is completed. Charring temperature measured in CCM experiment is about 380°C, which corresponds to the temperature that mass loss rate become slow and steady in thermalgravimetric analysis. The ignition temperature is about 350°C, which is basically the same as the temperature at which the mass loss rate reaches its maximum value in the thermalgravimetric analysis. It can be considered

that when the generation rate of volatile gas reaches its maximum, the specimen is ignited and starts to burn.

3.3 Moisture Content

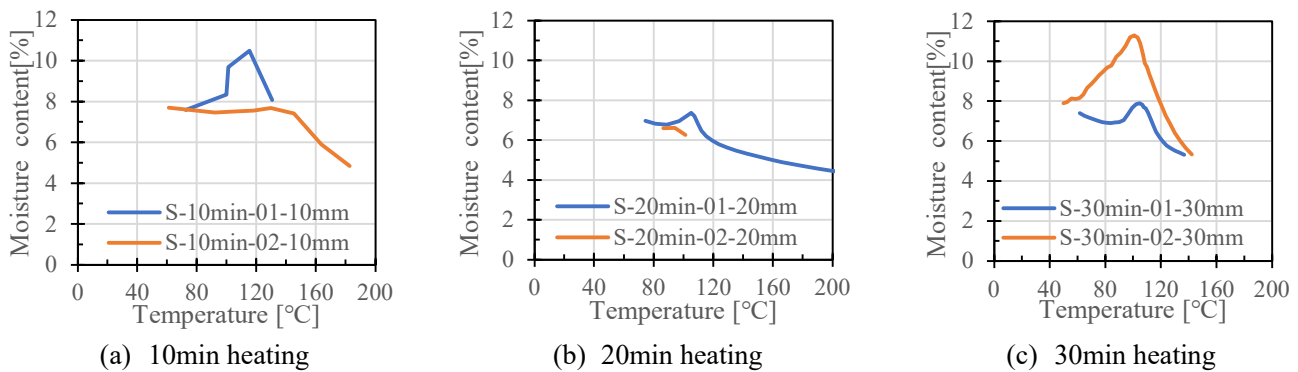
Results of moisture content measurement shows in **Figure 14**. Only results measured by insulation resistance testers were properly measured and shown here. According to **Fig.14 (a)~(e)**, moisture contents start to increase at about 60~80 °C. After reaching the peak value at about 100~120 °C, moisture content starts to decrease. Although moisture contents differed by specimens, local temperature at the peak value of moisture content is almost the same, e.g., 100~120 °C. This temperature is thought to be the boiling point of liquid water in wood. Almost all the experiments followed this tendency, except at 20 mm location in S-40-1. Moisture content at this location showed unrealistic increase at about 40°C. This may be caused by the malfunction of moisture sensor.

The increase of moisture content is caused by re-condensation as pointed out by other researches such as [36]. After specimen were heated, vaporization of liquid water near heated surface occurs, and the liquid water will turn to water vapor. Water vapor will move towards the non-heating surface due to pressure gradient. When water vapor contact with low temperature locations, condensation occurs at these locations, leading to an increase in water content at these locations. As long as the temperature near the surface is still high and liquid water still exists, evaporation will continue. This will cause the moisture content to continue to increase at a distance from the heating surface. Meanwhile, temperature at internal locations will continue to rise during the heating process due to heat conduction. Therefore, the temperature-moisture content relationship showed in **Figure 14** will express a tendency for the moisture content to increase with increasing temperature.

Results of moisture contents showed strong temperature dependence. Besides the peak period, moisture content decreased continuously at temperatures below about 60~80 °C. However, the phenomenon of moisture decreasing at 60~80°C did not appear in large scale experiments, while using same type of moisture sensor and calibration equation conducting moisture measurement on glue laminated larch[37]. This phenomenon were not observed on large-scale experiments using same moisture sensor on concrete neither[38], or different types of moisture sensors on wood[14][15]. This is probably because for large scale specimens, the size of heating surface is very large, and the moisture transfer can be considered as one-dimensional process that only occur in thickness direction. But in cases of small-scale tests where the dimension of heating surface is close to the thickness of specimen, moisture transfer in other direction (parallel to heating surface) may be significant. Since the permeability of wood in axial direction (which parallels to heating surface in both cross grain and straight grain specimen) is often above 1000 times greater than those in tangential and radial directions[39], the decrease in moisture contents observed in this experiment might be caused by the movement of liquid water in the direction parallel to heating surface.

Times at peak of moisture content at each location (besides S-40-1, at 20mm) are shown in **Figure 14(f)**. The average moisture peak moving speed is about 1.30 mm/min, according to the slope of regression line in **Figure 14(f)**. Although the peak values shown in **Figure 14(a)~(e)** varies by experiments and locations considerably, time to peak moisture content has a fairly small scatter. Relation between time to peak water content and depth from heated surface is linear.

It is worthy to note that regression line in **Figure 14(f)** did not pass the origin (0,0), which means that peak moving speed at 0~10 mm is different to other locations. Combustion of wood and pyrolysis gas at the initial stage after heating leads to rapid temperature increase, which also influenced moisture transfer. This leads to the phenomena that peak moving rate of moisture content at first 10mm is higher than those in other locations.



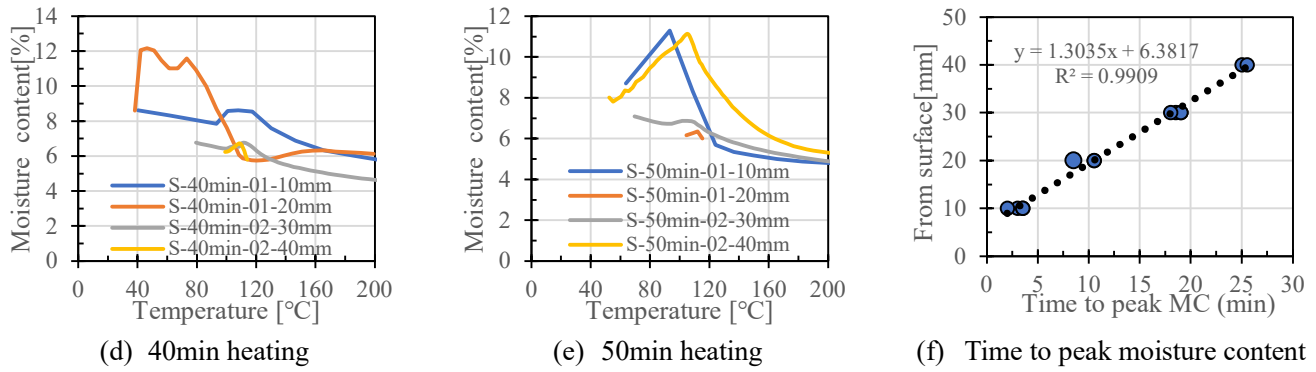


Figure 14: Measurement result of moisture content

4 Conclusions

In this paper, cone calorimeter tests were conducted on 20 glue laminated larch specimens to investigate heat and moisture transfer, burning behavior and charring behavior under heating by a cone calorimeter. Internal temperature, moisture content and heat release rate were measured during experiments. Charred depth and colored depth of each specimen were measured after experiment. Charring and coloring temperatures were calculated using measured temperature histories, charred depths, and colored depths.

Temperature creep was observed to start at about 100 °C, which is thought to be caused by phase change of water. The duration of temperature creep increased as the distance from heated surface because the heat flux was relatively small and moisture content was larger at locations near rear surface. As a result, time to vaporize liquid water increased. Internal temperatures of straight grain specimens are slightly higher than those cross-grain specimens. This is thought to be caused by the difference of direction of annual rings.

Peak heat release rate of each specimen was observed right after ignition with a value of about 150 kW/m². The heat release rate decreased to about 50 kW/m² within 5 minutes and maintained constant value afterwards, regardless of heating duration. Heat release rate of cross grain samples is slightly higher than straight grain samples.

Moisture content was measured by electrical resistance method. Although the measured moisture content varied by experiments, the relation between temperature and moisture distribution is almost identical. Moisture content started to increase at about 60~80 °C, and the peak of moisture content was reached at about 100~120 °C. After reaching the peak value, moisture content starts to decrease. Peak moisture content was thought to be the point that vapor condensation changes to liquid water vaporization. Time for moisture content to reach to peak values increased with depth linearly. Moving rate of peak water content was about 1.30 mm/min according to the regression result. The moving rate at 0~10mm is larger than this value due to intense heat flux.

Charred depth, colored depth and burnt-out depth increased according to heating duration. Charring rate was 0.72~0.76 mm/min. similar to results reported in previous large-scale tests. Coloring rate was 0.98~1.00 mm/min. Average coloring and charring temperatures at cross grain specimen and straight grain specimen were very close, at about 260 °C and 380 °C, respectively. Charring temperature estimated in this work is much higher than previously reported results.

Statements and Declarations

Competing Interests: The authors have no relevant financial or non-financial interests to disclose.

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