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A STUDY ON MOISTURE MIGRATION IN THE MULTIPLE DIRECTION IN LAMINATED GLULAMS EXPOSED TO FIRE INCLUDING MOISTURE MIGRATION ACROSS FINGER JOINTS AND ADHESIVE LINES

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ABSTRACT: Moisture content affects mechanical strength of wood as well as its temperature. Also, moisture migrates from heated sides. Therefore, mechanical strength of laminated timbers exposed to fire could decrease due to aggregation of moisture in load-bearing part. Moreover, laminated timbers include finger joints and adhesive lines which could make moisture migration more complex. It is important to investigate range in which moisture migrates and whether moisture migrates across finger joints and adhesive lines. In this paper, three types of laminated timbers were heated for 90 minutes according to the ISO834 standard heating curve in a small furnace. By measuring moisture content and temperature during heating and cooling, moisture migration in the multiple direction and across finger joints and adhesive lines was clarified. As a result, following moisture migration was suggested. Moisture migrated into the inner part and along the longitudinal direction. Also, moisture migrated across finger joints in heated side although finger joints hindered moisture migration in unheated side. Moreover, moisture migrated across the first adhesive line which was located in heated side although adhesive lines which were located further than the first adhesive line hindered moisture migration.

KEYWORDS: laminated timbers, small furnace, moisture content, finger joint, adhesive line

1 – INTRODUCTION

With the increase of wooden structures, their mechanical strength during and after fire needs to be predicted. There is a relationship between moisture content and Modulus of elasticity of wood [1]. Kaku et al. [2] reported that if moisture content is under 30% and temperature is under 95℃, Young's modulus and bending strength of Japanese cedar (*Cryptomeria Japonica*) decreased as moisture content increased. As for moisture migration, Yamamoto et al. [3] suggested that mechanical strength decreased due to the aggregation of moisture inside the wooden structural members exposed to fire heating despite the large remaining cross-sectional area. Kimura et al. [4] showed that moisture migrated into the inner part and along the longitudinal direction near the end of the furnace in full-scale laminated timbers exposed to fire heating.

From above, moisture migration into the inner part and along the longitudinal direction can occur in laminated timbers exposed to fire heating. This could lead to reduction of structural strength in load-bearing part. Moreover, if finger joints and adhesive lines hinder moisture migration, areas with high moisture content could occur locally. This could lead to significant reduction of structural strength there. It is important to clarify range in which moisture migrates in laminated timbers considering finger joints and adhesive lines.

Thus, in this paper, three types of laminated timbers made of Japanese cedar were heated to clarify moisture migration in the multiple direction and across finger joints and adhesive lines in detail during heating and cooling assuming a fire as shown in ***Fig. 1***.

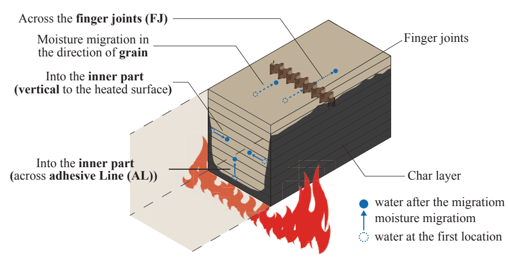

***Figure 1**. Schematic image of moisture migration in heated laminated timbers*

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2 – EXPERIMENTAL METHOD

2.1 PURPOSE

Three types of laminated timbers made of Japanese cedar, V series, V-FJ, and AL, were heated in a small furnace to clarify moisture migration into the inner part and across finger joints and adhesive lines. V series were prepared to clarify moisture migration in the multiple direction. V-FJ was prepared to clarify moisture migration across finger joints. AL was prepared to clarify moisture migration across adhesive lines. By measuring moisture content and temperature, moisture migration was clarified.

V200 and AL were left to cool in the furnace as long as possible until temperature in each measuring point stabilized. This is because moisture migration was speculated to occur at deeper locations than 110mm during cooling.

2.2 OUTLINE OF TESTS

Fig. 2 shows schematic diagram of the small furnace and the specimen. A part of the bottom surface within 250mm from the left end was heated to clarify moisture migration along the longitudinal direction. As shown in **Table 1**, the heated area means a zone over the heated surface. The heated side means a zone near to the bottom surface.

Using a small furnace in the Forestry and Forest Products Research Institute, all specimens were heated for 90 minutes according to the ISO834 standard heating curve. Then, V90, V110, and V-FJ were left to cool in the furnace for 180 minutes. V200 and AL were left to cool in the furnace for 390 minutes. V200 was set off after cooling for 370 minutes because of the risk of support materials getting fire. BSSR 1300 AS board was used as an inner covering material of the front wall of the furnace for V90, V110, and V-FJ.

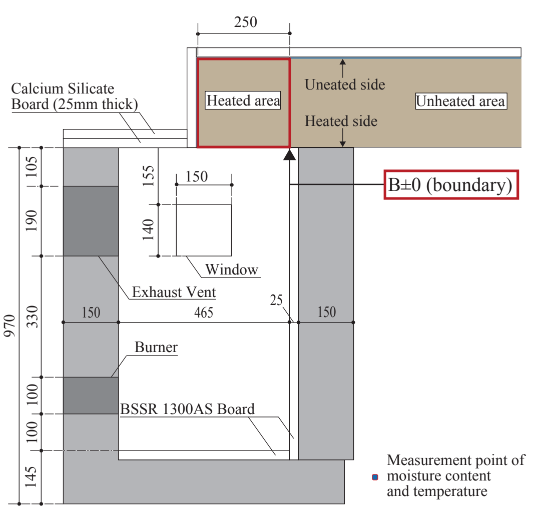


Figure 2. *Schematic diagram of small furnace and specimen (mm)*

2.3 OUTLINE OF SPECIMENS

Table 1 shows the composition of each type of specimens, measurement surface, and heated surface. **Table 2** shows layout of each specimen and its measuring points. As shown in **Table 1**, in V series and V-FJ, laminated timbers were set vertically to the heated surface. V-FJ had finger joints outside the furnace. In AL, adhesive lines were set parallel to the heated surface. All specimens were bonded with resorcinor resin adhesive. Its application amount was above 300 g/m^2.

In V90, V110, and V-FJ, four surfaces except for the bottom and the unheated end grain were covered with silicone sealant, polypropylene film, and calcium silicate board having a thickness of 25mm to prevent heat and moisture vapor be released. In V200 and AL, the same surfaces were covered with epoxy resin having a thickness of 4mm, aluminum foil, and calcium silicate board having a thickness of 25mm.

Moisture sensors and K-type thermocouples were set for each measuring point to measure moisture content and temperature as shown in **Table 2**. Dynamic moisture content measurement system [5] was used to measure moisture content. Measuring points were set on the centered cross-section as shown in **Table 1**.

Table 1. *Composition of laminated timber specimens*

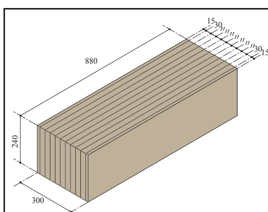
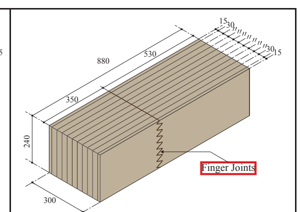
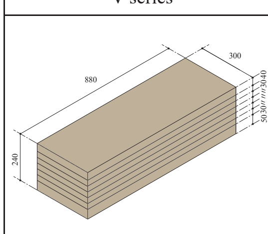
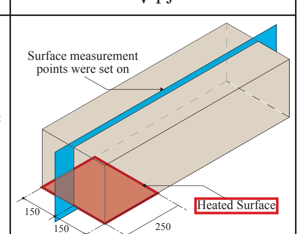
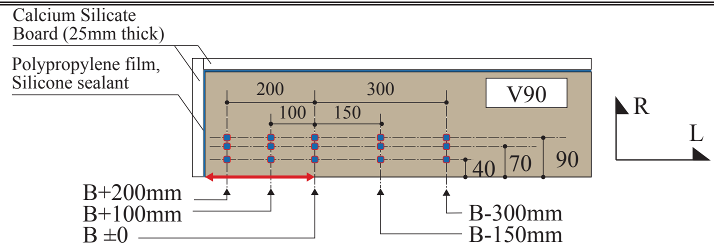
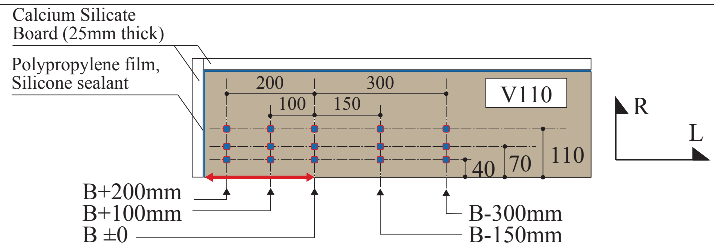
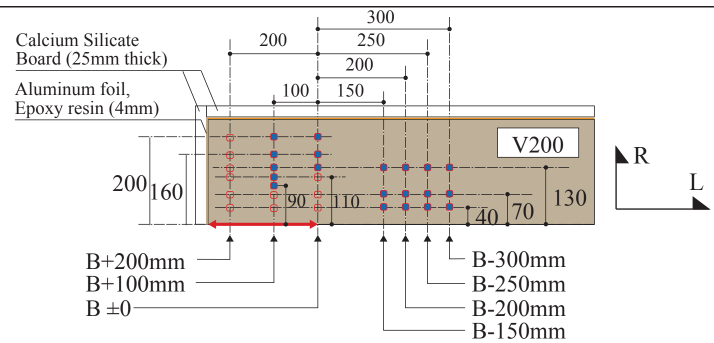
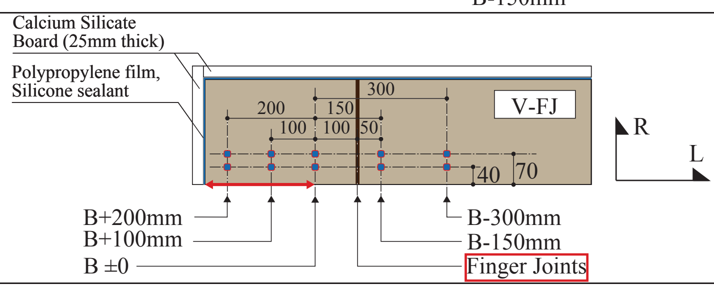
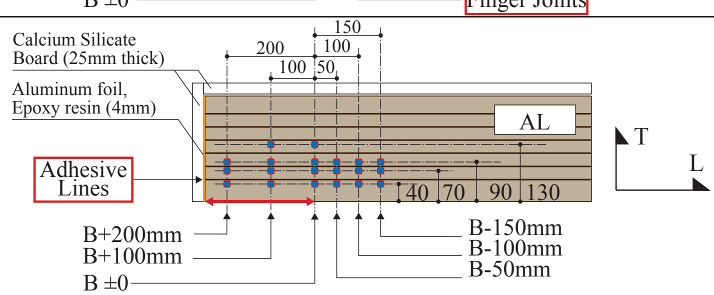
	
V series	V-FJ
	
AL	Measurement surface and heated surface

Table 2. Layout of specimens and measuring points

Direction of laminated timbers	Name of specimens		Layout of specimens and measuring points (L: longitudinal, R: radial, T: tangential)	Depth of measuring points (deepest/ shallowest)	
				Heated area	Unheated area
Vertical to the heated surface	**V series**	**V90**		90mm/40mm	
		V110		110mm/40mm	
		V200		200mm/ 90mm	130mm/ 40mm
	V-FJ (finger joints)			70mm/40mm	
Paralell to the heated surface	**AL (adhesive line)**			130mm/ 40mm	90mm/ 40mm

(filled blue square) Measuring points of moisture content and temperature	(open red square) Measuring points of temperature

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Measuring points of each specimen are set as follows. In this paper, depth shows distance from the heated surface.

(1) V series

V series except for the heated area of V200 had measuring points at the depth of 40mm and 70mm in common. V90 and V110 had measuring points at the depth of 90mm and 110mm respectively. V200 had measuring points at the depth of 130mm in all areas and at the depth of 160mm and 200mm in the heated area. This is because it was predicted that moisture would migrate to further locations than the depth of 110mm during cooling. Also, V200 had measuring points at B-200mm and B-250mm because it was predicted that moisture would migrate between B-150mm and B-300mm.

(2) V-FJ

V-FJ had measuring points at the depth of 40mm and 70mm. Finger joints were set at 100mm outer away from the heating boundary. This is because it was predicted that moisture would migrate along the longitudinal direction in the unheated area.

(3) AL

AL had measuring points at the depth of 40mm, 70mm, and 90mm in all areas and at the depth of 130mm at B+100mm and B±0. Adhesive lines were set across the measuring points as shown in **Table 2**. Also, AL had measuring points at B-50mm and B-100mm because it was predicted that moisture would migrate into the inner part near the heated area.

3– TEST RESULTS AND DISCUSSION

Results are shown as ***Fig. 3~7***. In ***Fig. 3~7***, MC means moisture content and the value is in the left axis. T means temperature and the value is in the right axis.

In this paper, measuring points are written as (cross-section, depth). Moisture content or temperature of each measuring point are written as "MC depth" or "T depth" with its depth (mm) from the heating surface.

3.1 MOISTURE MIGRATION IN THE MULTIPLE DIRECTION (V SERIES)

3.1.1 MOISTURE CONTENT AND TEMPERATURE (V90 AND V110)

As shown in ***Fig. 3*** and ***Fig. 4***, in the heated area, moisture content at the depth of 70mm, 90mm, and 110mm started increasing after temperature reached to 100°C and moisture content started decreasing at shallower locations. This suggests that moisture evaporated as temperature increased, migrated to the unheated side, and was absorbed there. Therefore, it was suggested that moisture migrated into the inner part within the depth of 110mm. Similar moisture migration was also measured by heating one side of cubic made of spruce or beech by the custom experimental set-up [6].

This result also showed possibilities that moisture could have migrated further than the depth of 110mm because T110 at B+100mm exceeded 100°C during cooling.

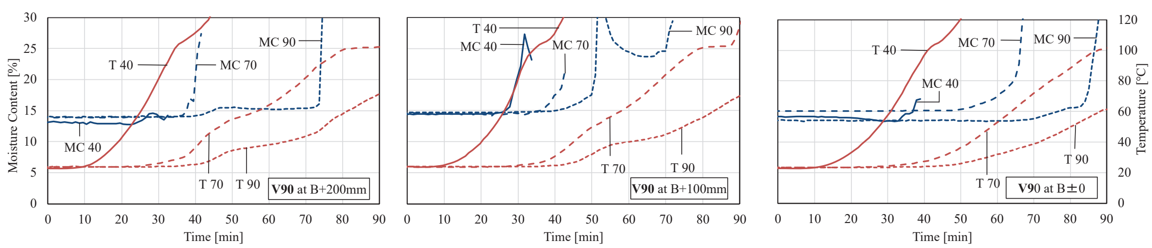

Figure 3*. Moisture content and Temperature of V90*

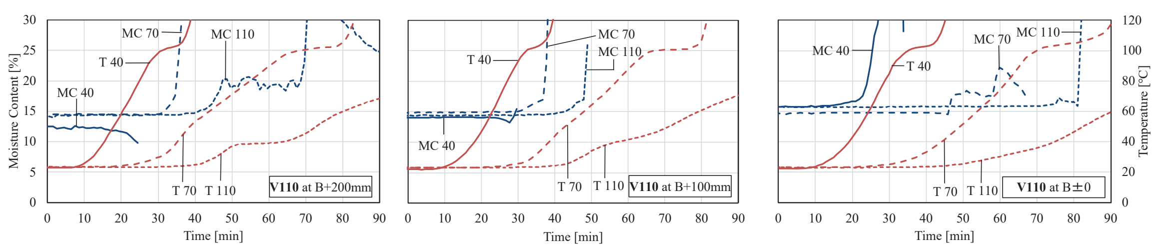

Figure 4*. Moisture content and Temperature of V110*

3.1.2 MOISTURE CONTENT AND TEMPERATURE (V200 IN THE HEATED AREA)

As shown in ***Fig. 5***, at B+100mm, T130 exceeded 100°C. At B+100mm, MC160 did not increase although T160 reached to 87.1°C. However, at B±0, MC130 started increasing when T130 exceeded 78.8°C. From above, moisture evaporated at (B+100mm, 130mm). However, if moisture vapor migrated from there to (B+100mm, 160mm), MC160 at B+100mm could have increased. This is because moisture vapor could have been absorbed at (B+100mm, 160mm) in the same way as moisture vapor was absorbed at (B±0, 130mm) as temperature increased. Considering that MC160 at B+100mm did not increase, moisture did not reach to (B+100mm, 160mm). Therefore, it was suggested that moisture migrated into the inner part within the depth of 160mm.

MC90 and MC110 of V200 at B+100mm did not increase although MC90 of V90 and MC110 of V110 at B+100mm increased. There was a possibility that there were some difficulties with reproducibility.

3.1.3 MOISTURE CONTENT AND TEMPERATURE (V200 IN THE UNHEATED AREA)

As shown in ***Fig. 5***, the further from the heating boundary, the later moisture content increased. MC40 and MC70 at B-250mm and MC130 at B±0 increased while MC40 and MC70 at B-300mm and MC130 at B-150mm were constant. Also, temperature decreased during cooling without reaching to 100°C. From above, moisture vapor from the heated area was absorbed at some measuring points. However, moisture did not migrate by evaporating from each measuring point. Therefore, it was suggested that moisture migrated along the longitudinal direction within 300mm outer away from the heating boundary at the depth of 40mm and 70mm and within 150mm outer away from the heating boundary at the depth of 130mm.

3.2 IINFLUENCE OF FINGER JOINTS-MOISTURE CONTENT AND TEMPERATURE (V-FJ)

As shown in ***Fig. 6***, moisture content and temperature of V-FJ is shown with solid lines. Those of V90 are shown with dashed lines.

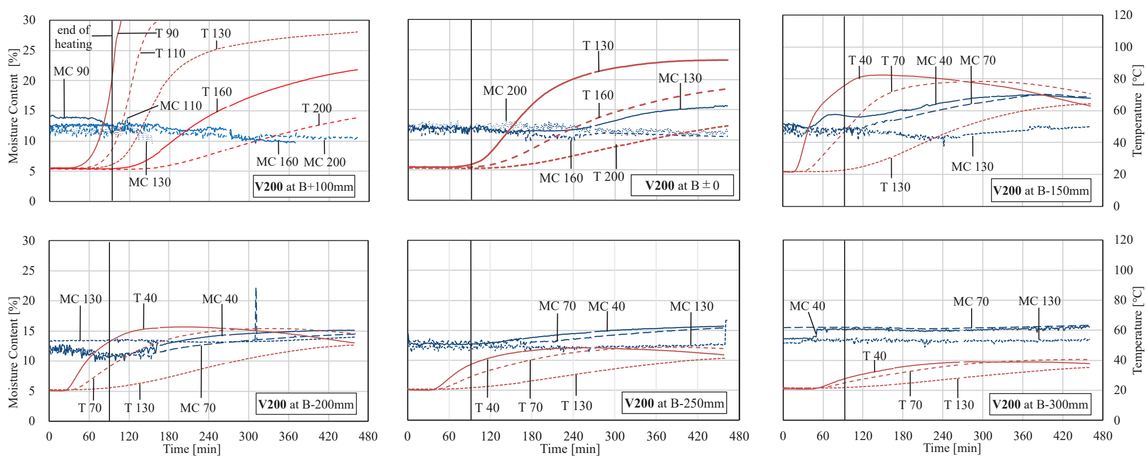

Figure 5. *Moisture content and Temperature of V200*

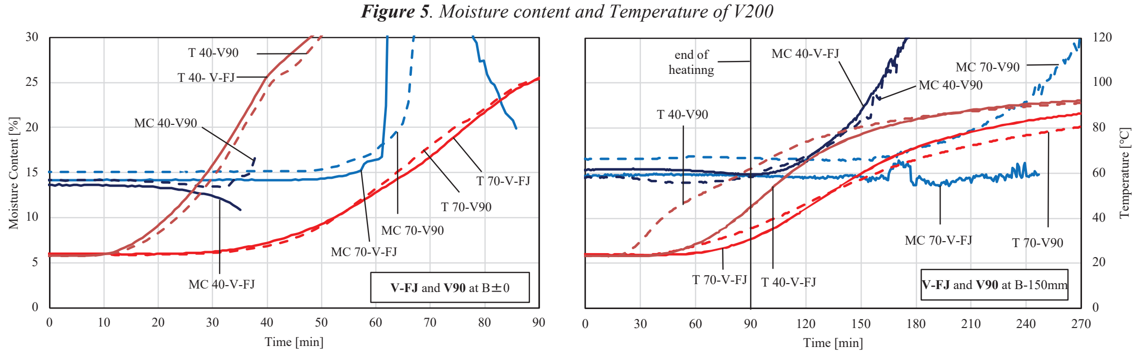

Figure 6. *Moisture content and Temperature of V-FJ and V90*

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At the depth of 40mm, comparing V-FJ with V90, moisture content and temperature of each showed the same tendency. Both MC40-V-FJ and MC40-V90 at B-150mm exceeded 30%. Therefore, it was suggested that moisture migrated along the longitudinal direction across finger joints at the depth of 40mm.

At the depth of 70mm, MC70-V-FJ at B-150mm did not increase although MC40-V-FJ and MC70-V90 at B±0 and MC70-V90 at B-150mm exceeded 30%. Comparing V-FJ with V90, temperature at the depth of 70mm showed the same tendency. Therefore, it was suggested that finger joints hindered moisture migration along the longitudinal direction at the depth of 70mm.

Enough temperature gradient which caused moisture migration across finger joints could have occurred in the heated side considering that moisture migrates by temperature gradient [7].

3.3 INFLUENCE OF ADHESIVE LINES

3.3.1MOISTURE CONTENT AND TEMPERATURE (AL IN THE HEATED AREA

Table 3. shows the increase of moisture content of AL at each measuring point. The increase of moisture content shows difference between initial moisture content and maximum moisture content.

As shown in ***Fig. 7***, as for the depth of 70mm, MC70 at each of B+200mm and B+100mm increased as T40 at each of B+200mm and B+100mm increased respectively. MC70 at each of B+200mm and B+100mm kept increasing after T40 at each of B+200mm and B+100mm reached to 100℃ respectively. In addition, as shown in **Table 3,** the increase of MC70 at each of B+200mm and B+100mm was larger than the increase of MC40 at each of B+200mm and B+100mm. Therefore, it was suggested that moisture migrated into the inner part across the first adhesive line except for the heating boundary.

As shown in **Table 3**, at the depth of 90mm, there was no measuring point in which moisture content increased significantly larger than the average of the increase of moisture content. Also, at each cross-section, the increase of MC90 was less than the increase of MC70. This shows different tendency from the large increase of MC90 of V90 at each cross-section as shown in ***Fig. 3***. Therefore, it was suggested that the second adhesive line hindered moisture migration into the inner part.

At the depth of 130mm, MC130 at B±0 exceeded the peak of MC90 at B±0. However, transition of MC130 at B±0 did not follow transition of T90 at B±0. Therefore, it was suggested that the third and further adhesive lines hindered moisture migration into the inner part.

3.3.2MOISTURE CONTENT AND TEMPERATURE (AL IN THE UNHEATED AREA)

MC70 at B-50mm could not be measured. This could be because moisture sensors were not fixed firmly.

As shown in ***Fig. 7***, as for the depth of 70mm, MC70 at each of B-100mm and B-150mm increased as T40 at each

Table 3*. The increase of moisture content of AL*

Depth (mm)	Moisture content [%]						
	B+ 200mm	B+ 100mm	B±0	B-50mm	B- 100mm	B- 150mm	average
130	-	2.9	4.9	-	-	-	3.9
90	1.0	3.9	3.3	4.2	2.5	3.6	3.1
70	4.6	5.5	6.2	-	9.3	12.6	6.4
40	1.6	2.8	4.5	7.3	2.5	1.2	3.3

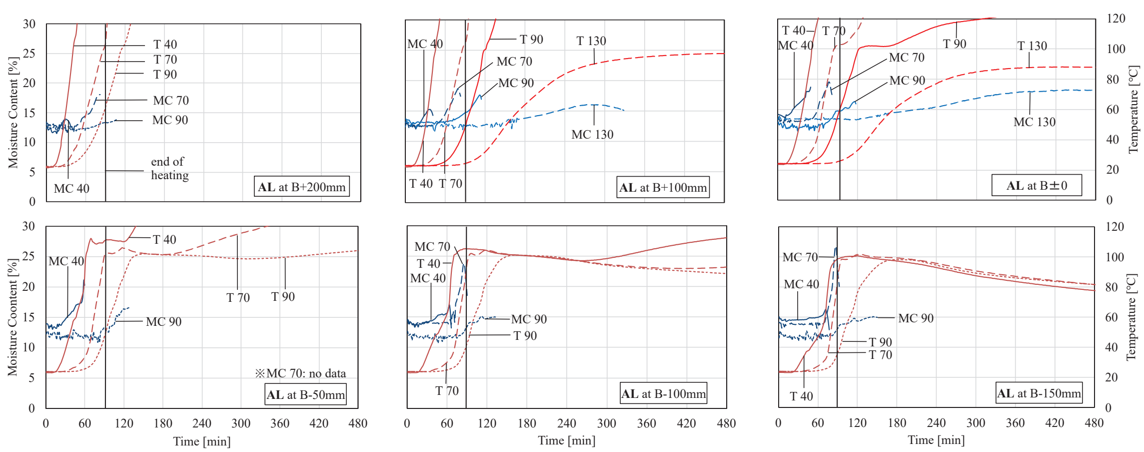

Figure 7*. Moisture content and Temperature of AL*

of B-100mm and B-150mm increased respectively. In addition, as shown in **Table 3,** the increase of MC70 at B-100mm and B-150mm was significantly larger than the increase of moisture content at the same depth in the heated area. Therefore, it was suggested that moisture migrated into the inner part across the first adhesive line.

As shown in **Table 3**, at the depth of 90mm, the same tendency was shown as in the heated area. Therefore, it was suggested that the second and further adhesive lines hindered moisture migration into the inner part.

4 – CONCLUSION

In this study, three types of laminated timber specimens made of Japanese cedar were prepared to clarify moisture migration in the multiple direction (specimen named as V series) and across finger joints (specimen named as V-FJ) and adhesive lines (specimen named as AL). V-FJ had finger joints at 100mm outer away from heating boundary.

All specimens were heated according to the ISO834 standard heating curve for 90 minutes and left to cool in the furnace. A part of bottom surface was heated to clarify moisture migration along the longitudinal direction from heated areas to unheated areas. By measuring moisture content and temperature, following moisture migration was suggested under the condition of this experiments. Depth shows distance from the heated surface.

(1) Moisture migration in the multiple direction (V series)
Moisture migrated both into the inner part within the depth of 160mm and along the longitudinal direction within 300mm outer away from the heating boundary at the depth of 40mm and 70mm and within 150mm outer away from the heating boundary at the depth of 130mm.
(2) Moisture migration across finger joints (V- FJ)
Moisture migrated across finger joints at the depth of 40mm. However, finger joints hindered moisture migration at the depth of 70mm.
(3) Moisture migration across adhesive lines (AL)
In all areas except for the heating boundary, moisture migrated into the inner part across the first adhesive line at the depth of 50mm. However, further adhesive lines hindered moisture migration into the inner part.

5 – ACKNOWLEDGEMENT

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