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Bonding Performance of Adhesives with Lamina in Structural Glulam Manufactured by High Frequency Heating System[1]

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ABSTRACT

The bonding performance of two types of wood adhesives, namely phenol-resorcinol-formaldehyde (PRF) resin and melamine-urea-formaldehyde (MUF) resin for glued laminated timber manufactured by high frequency (HF) heating was evaluated. The HF heating system consists of HF oscillator with dielectric heating system for curing adhesives, and hydraulic press system for clamping glued laminated timber. The designed frequency and output power of the HF system was as 5 MHz and 60 kW, respectively. To verify dielectric heating mechanism under HF oscillation, the heat loss factors of laminae and adhesives were measured. The results show that it is possible to selectively heat adhesives for their curing due to the remarkably higher loss factor of the adhesives than those of wood laminae. The temperature of adhesive in the bonding line reached up to the set temperature within a few seconds by high frequency oscillating, which advanced the curing of adhesive afterwards. The bonding performance, such as shear strength of bonding line, water soaking delamination, and boiling water soaking delamination of PRF resin met the requirement of Korean Standard (KS), however the MUF resin did not meet the KS requirement of boiling water soaking delamination. These results indicate that the HF heating system is successful to manufacture glued laminated timbers with PRF resins to meet the bonding requirements.

Keywords : glued laminated timber, high frequency, bonding performance, melamine-urea-formaldehyde resin, phenol-resorcinol-formaldehyde resin

1. INTRODUCTION

The demand of structural wood and wood-based materials in Korea have been increased considerably due to the preference of eco-friendly residential environment. The constructions of light

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frame construction that had been introduced around at the end of 1980s were consistently increased until the early 2000s. However, the increasing demand of light frame construction was slowed down in Korea, because of differences between light frame construction and the traditional Korean timber building, Hanok, in terms of exposure of timber as interior material though it is structural member. To keep the timber demand and environmentally friendly timber construction increasing in Korea, Korea Forest Research Institute (KFRI) developed modernized timber construction model which imported advantages of the traditional Korean timber building and the industrialized system from abroad, such as precut system. The modernized timber construction requires big dimension solid wood or engineered wood including glued laminated timber. Based on these efforts, 12,380 timber buildings were permitted in 2014 and it was more than 8 times than those in 2002 (Ministry of Land, Infrastructure and Transport, 2014). Recently high-rise and large scale wooden buildings in Europe and North America are being constructed by newly developed engineered wood product called cross laminated timber (CLT) which are structural wooden panel member for large-scale timber construction.

The domestic manufacturing method of structural glued laminated timber was done mainly by cold press curing systems. For manufacturing structural glulam, phenol-resorcinol-formaldehyde (PRF) resin is usually used because of its high bonding properties under wet condition, even though it is relatively expensive (Messmer, 2015; Shim *et al*., 2005; Kim and Hong, 2011). In the cold press system, adhesive spreaded laminae were pressed by clamps up to certain pressure and cured for more than 24 hours under room temperature. The long curing time results in low productivity and increases the unit cost of structural glulam production. Therefore, it is necessary to develop short term manufacturing system which can use low cost adhesives and reduce curing time.

The principle of HF dielectric heating is a process in which a high-frequency alternating electric field, or radio wave heats a dielectric material. At higher frequencies, this heating is caused by molecular dipole rotation within the dielectric field. The heat generation is related to the relative loss factor of materials. Yang *et al.* (2014) reported that the relative dielectric constant and the loss factor was changed by the oscillated frequency and the selection of frequency range was important to heat materials. The HF heating system has already commercially been used in the manufacturing of glued laminated board or laminated veneer lumber (LVL).

The objectives of this research are to develop manufacturing process of structural glulam by oscillated HF, to improve the productivity of structural glulam with economic efficiency. Therefore, the bonding performance assessment of the suitable adhesives in the HF heating system was carried out.

2. MATERIALS and METHODS

2.1. Materials

To evaluate bonding performance of adhesives of glulam manufactured by HF, four major softwood species in Korea such as Japanese larch (*Larix kaempferi* Carriere), Korean pine (*Pinus koraiensis* Siebold & Zucc.), Korean red pine (*Pinus densiflora* Siebold & Zucc.) and Japanese cedar (*Cryptomeria japonica* D.Don) were selected for this research. The lamina was 30 mm thick, 190 mm wide, and 1,800 mm long. The average moisture content was 10%. The melamine -urea-formaldehyde (MUF) resin and phenol-resorcinol-formaldehyde (PRF) resin were used as adhesives. The PRF adhesive was mixed with para-formaldehyde as hardener. The MUF adhesive consisted of MUF resin, hardener (ammonium chloride), and wheat flour. The solid content rate, the viscosity and the pH of MUF resin was 54.72%, 80 cPs and 10.47 respectively.

2.2. HF Heating System and Delamination Test

The structural glulam manufacturing system by the HF heating is composed of dielectric heating system to heat glue for cure and hydraulic press system to press laminae. The targeted frequency for HF oscillator was set as 5 MHz and the output power was set as 60 kW. The HF heated structural glulam was manufactured with 5 laminae of 30 × 190 × 1,800 mm to manufacture 150 × 190 × 1,800 mm structural glulam. To equalize dielectric heating under constant electric field, the glued laminae were arranged in the center of the press and polyethylene plates were filled in the remaining area of press (Fig 3-a). The glued laminae were pressed with 10 kgf/cm^2 pressure. Then the bonding lines were heated by HF oscillator. Based on the pretest results of bonding line, the applied oscillating conditions was set as 2 A of anodic current capacity, 10 minutes of applied time and 10 minutes of cooling time.

To assess bonding performance, water soaking and boiling water soaking delamination test and the shear block test were conducted according to the procedure of the KS F 3021.

2.3. Measurement of Relative Dielectric Properties

The relative dielectric properties of Japanese larch, Korean red pine, Korean pine and Japanese cedar in the transverse direction were measured. Twelve specimens (8 × 100 × 100 mm) per species were prepared for measurement of relative dielectric properties. The relative dielectric constant was measured by Precision Impedance Analyzer (4294A, Agilent) which can oscillate and analyze the range of radio wave. The accessory to measure dielectric properties of lamina was Dielectric Test Fixture (16451B, Agilent) and accessory for adhesives was Liquid Test Fixture (16452A, Agilent), respectively. The relative dielectric properties affect dielectric heating speed, and

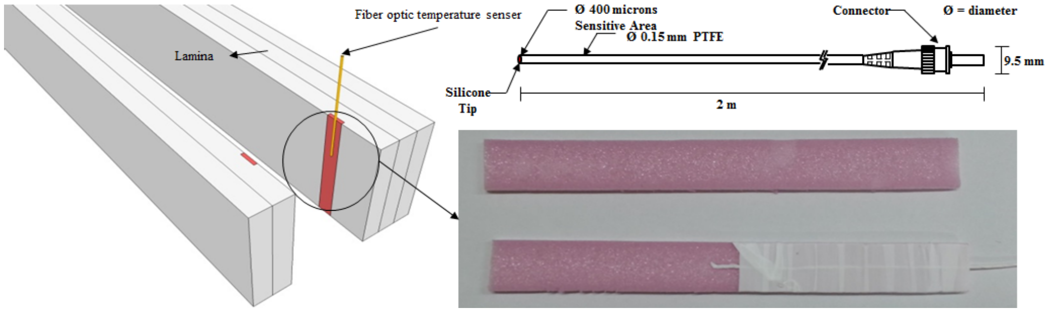


Fig. 1. Temperature measurement of bonding line of glulam using fiber-optic temperature sensor.

other factors of relative dielectric properties are power density, and density and specific heat of dielectric material. The power density is the amount of supplied energy per unit time and it can be calculated by following Eq. 1 (Torgovnikov, 1993).

$$PD/d = (5.56\times 10^{-11})E^2 f\varepsilon_r'' \quad \cdots\cdots\cdots\cdots\cdots\cdots \text{Eq. 1}$$

where,
PD = Power density (W/m^2)
E = Electric intensity (V/m)
f = Frequency of external alternating electric field (Hz)
ε_r'' = Relative loss factor
d = Electrode spacing

In the assumption of no mass loss by moisture evaporation in the material, the increment of inner temperature per unit time is calculated by Eq. 2 (Nelson and Kraszewski, 1990).

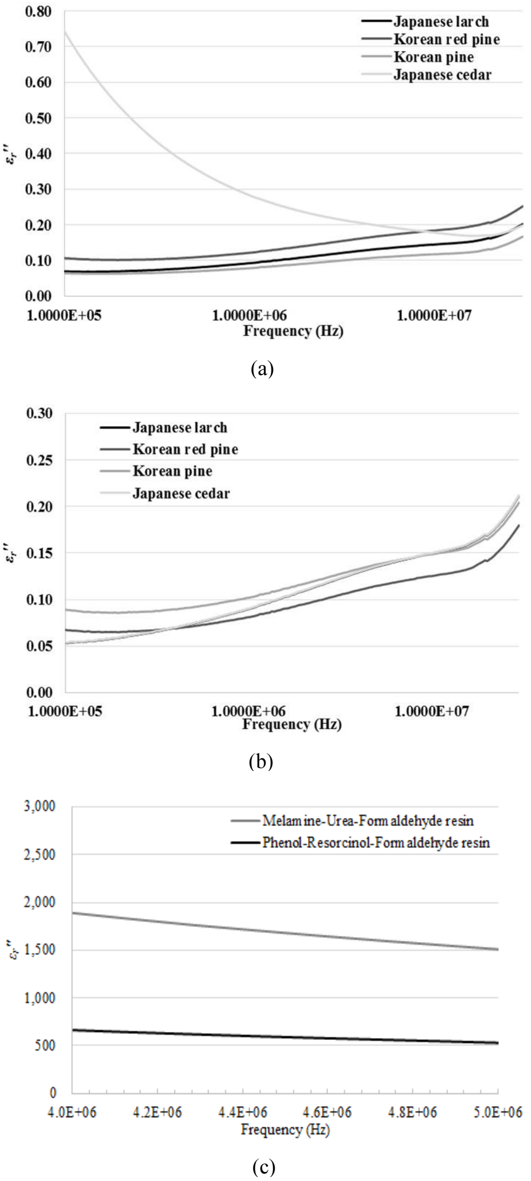
$$\frac{\Delta T}{\Delta t} = \frac{PD/d}{\rho c_p} = \frac{(5.56\times 10^{-11})E^2 f\varepsilon_r''}{\rho c_p} \quad \cdots \text{Eq. 2}$$

where,
ρ = Density of lamina(g/cm^3)
c_p = Specific heat(J/g℃)

The relative loss factor was measured in the range of the targeted high frequency range (100 kHz ∼ 30 MHz). The relative loss factors of species and adhesives were analyzed in the condition of 5 MHz frequency of HF oscillator.

2.4. Measurement of Bonding Line Temperature

The temperature of bonding line during oscillating HF was measured. The surface temperature of glulam was measured by infrared camera at the cross section of glulam. The variation of temperature of bonding line of during the oscillating HF was measured by fiber-optic temperature sensor (accuracy: ± 1℃). Fiber-optic temperature sensor was inserted in a styrofoam cast to prevent from breaking while pressure is applied. Inner lamina was grooved to install the sensor with styrofoam cast and then the adhesives were applied prior to measuring the bonding line temperature during the oscillating HF to manufacture structural glulam.



(a)

(b)

(c)

Fig. 2. Loss factor by wood species at 10% MC and types of adhesives under high frequency : (a) radial direction, (b) tangential direction and (c) adhesives.

3. RESULTS and DISCUSSION

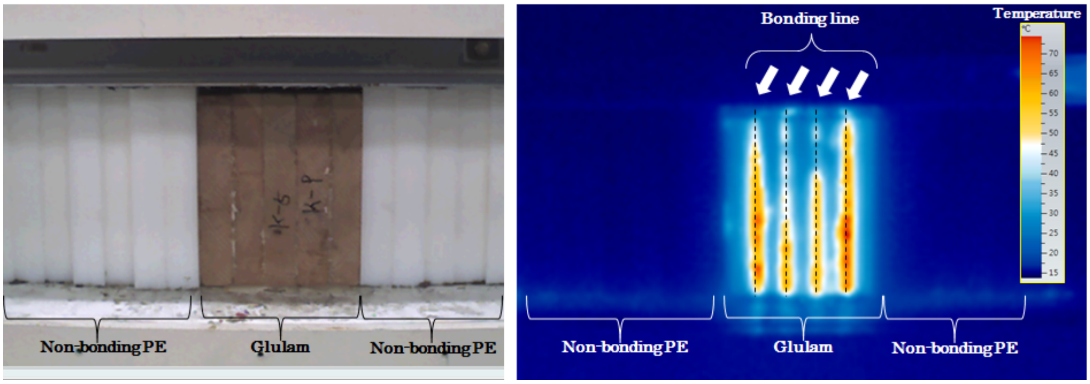
3.1. Relative Loss Factor of Dielectric Properties.

Temperature increment by dielectric heating speed is higher when the relative loss factor is increased. Fig. 2 shows transverse loss factor by wood species in the 100 kHz ∼ 30 MHz range of HF. As the high frequency increased, the loss factor of the radial and tangential direction of wood species increased except Japanese cedar. The loss factor was increased in the condition of higher HF. It is because of energy loss of wood species which induced by differences of higher frequency and polarization of polar molecules of wood species. The ranges of loss factor on radial direction of wood species were 0.05∼0.25 except Japanese cedar. In case of Japanese cedar the increment of the frequency resulted in the decrease of the loss factor in the radial direction (Fig. 2-a). In the tangential direction, loss factors of all four wood species were 0.05∼0.21. Based on the $\varepsilon_r''/\rho_{cp}$ of Japanese larch under the same high frequency condition, the relative values of Korean red pine, Korean pine and Japanese cedar were 1.21, 1.56, 1.65, relatively.

Loss factors of PRF and MUF resin were decreased with an increase of the frequency (Fig. 2-c). In the 4∼5 MHz range of high frequency, the average relative loss factor of MUF resin (ε_r'') was 2.84 times higher than that of the PRF resin. The value of $\varepsilon_r''/\rho_{cp}$ of PRF resin was 1.65 times higher than that of MUF resin. Comparisons of the values of $\varepsilon_r''/\rho_{cp}$ among

Table 1. Material properties related to dielectric heating under high frequency condition

Materials	Loss factor (ε_r'')	Density (ρ) g/cm^3	Specific heat ($_{cp}$) J/g℃	$\varepsilon_r''/\rho_{cp}$	Ratio
Japanese larch	0.13	0.568	1.67	137	1.00
Korean red pine	0.11	0.466	1.42	166	1.21
Korean pine	0.14	0.433	1.51	214	1.56
Japanese cedar	0.13	0.364	1.58	226	1.65
Phenol-Resorcinol -Formaldehyde resin	593	1.043	2.08	273,342	1994
Melamine-Urea -Formaldehyde resin	1,685	1.184	8.59	165,674	1209



(a) (b)

Fig. 3. Arrangement of glulam and PE (a), surface temperature measurement of cross section by infrared camera (b).

tested materials, the values of two resins were considerably higher than those of wood species (Table 1). A selective heating of the bonding line to cure the adhesive is possible due to a great difference between wood species and adhesives of $\varepsilon_r''/\rho_{cp}$ value.

3.2. Measurement and Comparison of Bonding Line Temperature

To identify selective dielectric heating of bonding line, inner and surface temperature was measured by fiber-optic temperature sensor and infrared camera, respectively. Fig. 3 (b) shows the images of the transverse section of Korean pine glulam by infrared camera when the oscillation of HF completed. The non-bonding PE plates were not heated and the surface temperature of extruded adhesive was higher than the wood laminae. The heat from the bonding line diffused into the laminae due to the difference of dielectric heating rate.

Table 2. Comparison of the bonding performance of adhesives of glulam prepared

Glulam	Types of adhesives					
	PRF resin			MUF resin		
	WSD[1] (%)	BSD[2] (%)	Shear strength (MPa)	WSD (%)	BSD (%)	Shear strength (MPa)
Japanese larch	2.22 (1.15)[3]	2.61 (0.72)	11.03 (0.10)	2.54 (0.28)	14.00 (0.60)	7.32 (0.75)
Korean red pine	1.10 (1.38)	2.89 (0.42)	8.58 (0.85)	12.89 (0.73)	42.47 (0.16)	6.94 (0.78)
Korean pine	0.69 (0.56)	0.64 (1.72)	9.74 (0.82)	8.83 (0.37)	24.46 (0.20)	6.16 (0.93)
Japanese cedar	0.73 (1.47)	2.34 (1.07)	9.31 (0.79)	0.00 (-)	9.95 (0.67)	5.31 (0.13)

[1] WSD : The ratio of water soaking delamination
[2] BSD : The ratio of boiling water soaking delamination
[3] The value in parentheses are coefficient of variation of the mean

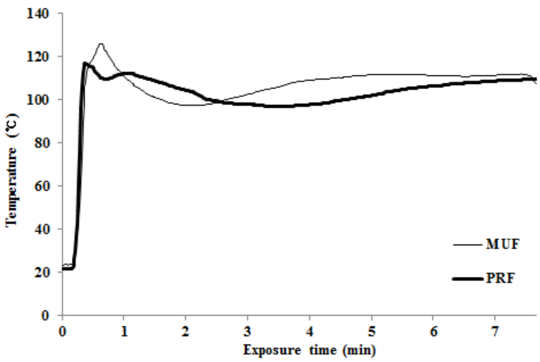


Fig. 4. Measured temperature profile of the bonding line by fiber-optic sensor (narrow line: MUF resin, bold line: PRF resin).

The temperature profiles of bonding lines in the Korean red pine glulam measured by fiber-optic temperature sensor were compared (Fig. 4). Under the condition of 2 A anodic current capacity and 10 minutes HF, the temperature of PRF resin went up to 126℃ in 20 seconds by dielectric heating. After the temperature reached 126℃, it decreased as the cure of PRF adhesive advanced. The time to reach the onset temperature of MUF resin adhesive was around 35 seconds.

After about 10 minutes of HF oscillation, the steam leaked from the bonding line. It seems that the rapid heating of the moisture in the adhesive and lamina results in turning free water into vapors near and in bonding lines, and then the vapor steam was leaked out as steam. After applying 10 minutes cooling, a defect or small diameter holes in the bonding line was observed due to the evaporation of steam leakage. Therefore, identifying the optimal condition of controling HF oscillation including time and intensity for specific wood species and adhesive types is necessary to manufacture structural glulam by HF heating.

3.3. Bonding Performance of Adhesives of Glulam

For the comparison of bonding performance by types of adhesives, Table 2 presented the water soaking delamination ratio (WSD), boiling water soaking delamination (BSD) and shear strength of glulam bonding line. In terms of delamination, PRF resin met Korean Standard (KS) requirement which was less than 5%. The block shear strengths of all four wood species glulam bonded with PRF resin adhesive also met KS requirement (Japanese larch : 7.1 MPa, Korean red pine and Korean pine : 5.9 MPa, Japanese cedar : 5.3 MPa).

In case of glulams bonded with MUF resin adhesive, the WSD of Japanese larch and Korean pine met the requirement of the KS, but there were no species to meet BSD requirement of the KS. After water soaking, the delamination of MUF resin bonded-glulams of Korean red pine resulted from leaking resin from laminae. The block shear strength of MUF resin bonded-glulams was lower than those of the PRF glulams, but it met the KS requirements. It is necessary to develop suitable content of melamine in the MUF resin adhesive to achieve BSD performance as structural glulam.

4. CONCLUSION

This study was carried out to evaluate bonding performance of adhesives of structural glulam under high frequency oscillating system for domestic major softwood species such as Japanese larch, Korean pine, Korean red pine, and Japanese cedar. The results of dielectric properties showed that it was possible to selectively heat adhesives for curing due to remarkably higher loss factor of the adhesives than those of wood laminae under the HF oscillating. The onset temperature of MUF and PRF resin under HF heating system was obtained within 5 minutes, indicating that the reduction of curing time could help increase the productivity of glulam manufacturing. The bonding properties of PRF and MUF resin bonded-glulams met the KS requirements except the boiling water soaking delamination of MUF resin. These results suggested that the water resistance of MUF resin bonded-glulams as structural glulam should be improved.

REFERENCES

Kim, K.H., Hong, S.I. 2011. Bonding performance of glulam reinforced with Textile type of glass- and aramid-fiber, GFRP and CFRP. Mokchae Konghak 39(2): 156～162.

Korean Standards Association, 2008. KS F 2160. Determination of resistance to soaking delamination for adhesive-bonded wood products

Korean Standards Association, 2013. KS F 3021. Structural glued laminated timber.

Messmer, A. 2015. Life cycle assessment of adhesives used in wood constructions. Master Thesis, Institute of Ecological System Design, ETH Zürich.

Ministry of Land, Infrastructure and Transport. 2014. Statistics of Building Permission Commencement Works.

Nelson, S.O., Kraszewski, A. 1990. Grain moisture content determination by microwave measurements. Transactions of the ASAE 33(4): 1303～1307.

Shim, S.R., Yeo, H.M., Shim, K.B. 2005. Evaluation of shear bond strength and adhesive bond durability of mixed species structural glued laminated timber. Journal of the Korean Wood Science and Technology 33(1): 87～96.

Torgovnikov, G.I. 1993. Dielectric properties of wood and wood-based materials. Springer, Heidelberg. ISBN 3-540-55394-0.

Yang, S.Y., Han, Y.J., Park, Y.G., Eom, C.D. Kim, S.J., Kim, K.M., Park, M.J. Yeo, H.M. 2014. Estimation of radio frequency electric field strength for dielectric heating of phenol-resorcinol-formaldehyde resin used for manufacturing glulam. Journal of the Korean Wood Science and Technology 42(3): 339～345.