

Bambang Subyakto · Toshimitsu Hata · Isamu Ide
Shuichi Kawai

Fire-resistant performance of a laminated veneer lumber joint with metal plate connectors protected with graphite phenolic sphere sheeting

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Abstract Creep under fire of laminated veneer lumber (LVL) joined with metal connectors was studied. The fire-resistant performance of LVL butt joints connected with metal plates protected with graphite phenolic sphere (GPS) sheeting was discussed. The GPS sheeting was overlaid on the joint in different sizes and locations. The joint was exposed to a burner with a top flame temperature of 800°C and loaded with a load of 200N to test for creep under fire. The results showed that the fire-resistant performance of the joint was markedly improved by the sheeting. The size and location of the GPS sheet significantly affected the time to rupture of the specimen, which was six times longer than that without GPS. Temperature measurements at the joint showed that the GPS sheeting distributed the heat along the surface and delayed failure. Thermographic images and analyses clarified the improvement in fire-resistant properties due to GPS.

Key words Laminated veneer lumber · Joint · Graphite phenolic spheres · Metal plate connectors · Creep test · Fire-retardant performance

Introduction

The demand for wood composites from fast-growing trees or waste wood has been increasing as timber resources in

natural forests decline. Among these materials, laminated veneer lumber (LVL) and oriented strand board (OSB) are promising as substitutes for structural timber and plywood, respectively. The application of such products as building materials depends, among other factors, on their fire-resistant performance.

The fire resistant performance of structural timber is important. Timber joints connected with metal plates are considered a weak point in a structure exposed to fire.¹ Several studies have been conducted on the properties of metal plate connectors,^{2,3} reinforced joints,⁴ and structural timber under fire.⁵ Some studies also have been reported on the fire-resistant performance of timber joints under loading.^{6–10} For example, Uesugi et al.⁹ show that the fire resistance of LVL joints improved when a drift pin joint with an insert-type steel gusset plate was applied or the joint was covered with wood plate.

Graphite phenolic sphere (GPS) is basically a mixture of carbon graphite and ceramic fiber with phenol-based resins, which has thermal anisotropy resulting in heat transfer in two directions. We previously demonstrated that a similar composite, carbon phenolic sphere (CPS) made from a mixture of carbonized wood and phenol formaldehyde resin, differs markedly in thermal properties in the horizontal compared to the vertical plane. These properties can be assumed to improve the fire resistance of joints covered with GPS.¹¹

The purpose of this research is to improve the fire resistance of LVL butt joints connected with metal plates covered with GPS. Thermograph analysis was conducted to clarify the mechanism of heat transfer on the surface of the joint. Attempts were made to improve the fire resistance of the joint.

Materials and methods

Materials and preparations

Commercial products of LVL (Douglas fir), from Micro-Lam of Trus Joist MacMillan Ltd. with an average density

B. Subyakto
R&D Center for Applied Physics, LIPI, Puspiptek Serpong,
Tangerang 15310, Indonesia

T. Hata (✉)
Wood Research Institute, Kyoto University, Uji, Kyoto 611-0011,
Japan
Tel. +81-774-38-3677; Fax +81-774-38-3678
e-mail: n50120@sakura.kudpc.kyoto-u.ac.jp

I. Ide
Lignyte Ltd., Sakai, Osaka 592, Japan

S. Kawai
Wood Research Institute, Kyoto University, Uji, Kyoto 611-0011,
Japan

of 0.585 g/cm^3 and a moisture content of 9%, were used. Samples 800 mm in length, 38 mm in width (flatwise), and 50 mm in height (edgewise) were cut into two 400-mm lengths. Metal plate connectors, gang nails of 18-gauge mild steel with a galvanized finish $79 \times 35\text{ mm}$ and 1.14 mm thick consisting of 20 teeth, were used to connect the LVL butt joint. The metal plate connector consists of four rows and five columns with 12 long (14.4 mm) and 8 short (11.0 mm) nails.

Two pieces of LVL, each 400 mm in length, were joined with two metal plate connectors, one on each side (flatwise). These connectors were pressed manually by a hydraulic press at a pressure of 4.9 MPa for about 3 s.

The GPS sheeting (Lygnite Ltd.), with a thickness of 1 mm and an average density of 0.67 g/cm^3 , contains about 20% phenol resin. The thermal constants of GPS were measured using a Laser Flash Thermal Analyzer (Ulvac Shinku-Riko TC-7000) horizontal and vertical to the plane of the specimen.¹¹ The results are as follows: Thermal diffusivity in the horizontal (H) direction was $0.0113\text{ cm}^2/\text{s}$ and in the vertical (V) direction $0.0015\text{ cm}^2/\text{s}$, thermal conductivity was 0.0053 W/K/cm (H) and 0.0007 W/K/cm (V), and heat capacity was 0.7002 J/g/K .

The GPS sheet was overlaid on the LVL joint at the metal plate connectors or underneath the joint by hot pressing at 180°C for 1 min at a pressure of 200 kPa. The size of the sheet was $50 \times 158\text{ mm}$ or $38 \times 158\text{ mm}$ at bottom (large), $35 \times 79\text{ mm}$ (medium), or $17.5 \times 39.5\text{ mm}$ (small), as shown in Fig. 1. GPS sheets were positioned in three ways: to cover both the sides and bottom (three sides), just the sides (two sides), or just the bottom (one side) of the joint.

Bending test

Bending tests at four points with the loading edgewise were conducted on solid LVL and LVL joined with metal plate connectors. The sample was 800 mm in length \times 50 mm in height \times 38 mm in width. The span was 750 mm with a crosshead speed of 5 mm/min. Ten replications were tested. The maximum load of each sample was determined, and 10% of the average value of the bearing load was used to test for creep under fire.

Test of creep under fire

Creep under fire was tested by applying a load and fire at the same time.^{12,13} The purpose of this test is to expose the sample specimens to both fire and load at the same time using a simple apparatus. In this test, fire or flame comes from one side. It is different from standard fire tests, for example the JIS A 1304 where the fire touches all surfaces of the sample. By one side flame (a spot flame), it is expected that the anisotropy effect of the GPS sheet could be observed with the help of thermograph observation.

The sample size was $800 \times 50 \times 38\text{ mm}$. Each sample was set with a span of 750 mm. Ten percent of maximum load as calculated from the bending test (i.e., a load of 200 N), was applied at the edge of the sample. The joint was exposed to

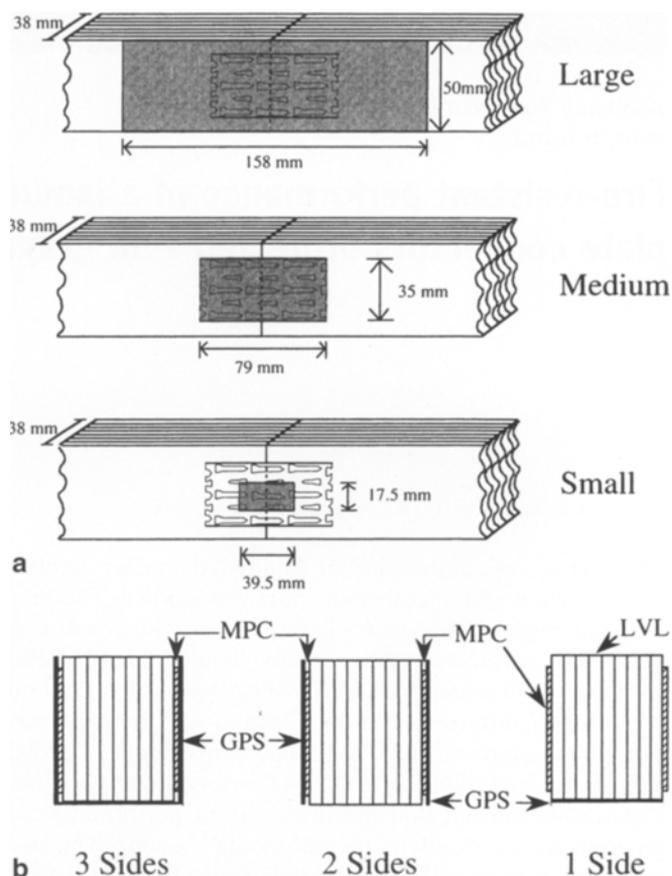


Fig. 1. Size (a) and location (b) of the graphite phenolic sphere (GPS) sheet on the laminated veneer lumber (LVL) joint. MPC, metal plate connector

fire from a burner with a flame length of 65 mm and top flame temperature of $800^\circ\text{--}850^\circ\text{C}$. Thermocouples were inserted into the butt joint by drilling small holes to measure the temperature. The thermocouples were located at the center of the butt joint, between the metal plate connector and LVL, and at the surface of the metal plate connector. These thermocouples were connected to a data logger to record the changes in temperature during the test. The room temperature was also recorded. Deflections of the samples were measured using a dial gauge and recorded manually every 2 min until the samples ruptured. The time to rupture was recorded for each sample. Three replications were tested for each condition.

Thermograph analysis

A thermograph apparatus (Thermal Video System 2000 ST, Japan Avionics) consisting of an infrared camera, an image processor, and a recorder was used. The camera was placed at the same height as and almost perpendicular to the observed joint at a distance of 50 cm. Carbon black was sprayed on the observed surface of the joint, and the radiation rate of the thermograph was set at 1. Calibration was done prior to the measurement by comparing with

thermocouple measurements. The distribution and changes of temperature on the surface of the joint during the test were recorded at intervals of 4min or of 16min for the samples covered on three sides with the large GPS sheet. Temperature range was set at 20°–300°C, as degradation of wood occurs below 300°C. The data and the images were analyzed by PicEd Avio Version 4.05 software (Japan Avionics).

Results and discussion

Bending strength of LVL

Table 1 shows the results of the bending test. The LVL solid without a joint has an average maximum load of 8600 N, and the value for LVL with a butt joint connected by metal plates was 2000 N. Therefore, in the test for creep under fire a 10% maximum load, 200 N, was applied to each sample. The average of the modulus of elasticity (MOE) of the LVL solid sample was 1.2×10^4 Mpa, and the modulus of rupture (MOR) was 67 MPa. For the samples with a butt joint, the average MOE and MOR were 4.6×10^3 MPa and 15 MPa, respectively. The MOE ratio for samples with and without a butt joint was 0.39, and that for the MOR was 0.23. The bending strength of the LVL with a joint has a lower standard deviation (less variation). The bending strength of the butt joint covered with a GPS sheet 50×158 mm on three sides (MOR 16 MPa, MOE 4.4×10^3 MPa) was similar to that of an uncovered butt joint. It can be said that the effect of the GPS sheeting on the bending strength of the LVL butt joint is negligible.

GPS sheeting as a fire protection for LVL joint

Deflection of LVL butt joint exposed to load and fire

In a wooden structure subjected to load and fire simultaneously, deflection is an important indicator of the brittleness (strength) of the material before failure occurs. Subjected to a constant load of 10% maximum load, the creep deflection of the structure is negligibly small. However, on exposure to fire, the deflection increases markedly. The effect of a large GPS sheet covering the LVL joint on

the creep deflection is presented in Fig. 2. The sheet delayed deflection. When LVL without protection was exposed to fire it burned quickly. Thus the GPS layer protected the LVL from fire and reduced deflection. The results were the same whether a large (50×158 mm), medium (35×79 mm), or even a small (17.5×39.5 mm) GPS sheet was applied. Therefore, GPS sheeting effectively reduces the deflection rate during the fire test under loading. The result may be useful in terms of the structural application of LVL, especially in the event of fire.

As expected, the location of the GPS sheet at the joint affected the deflection of the LVL. This could be related to the surface that was exposed (i.e., the bottom) and the size of the sheet used. A sheet 50×158 mm (large) covering three sides produced the smallest deflection followed by that covering one side and two sides. The flame was directed at the bottom of the joint; therefore the deflection of joints covered on this surface was less than that of joints covered on only the sides. A similar trend was observed with the sheet 35×79 mm (medium). However, with the small (17.5

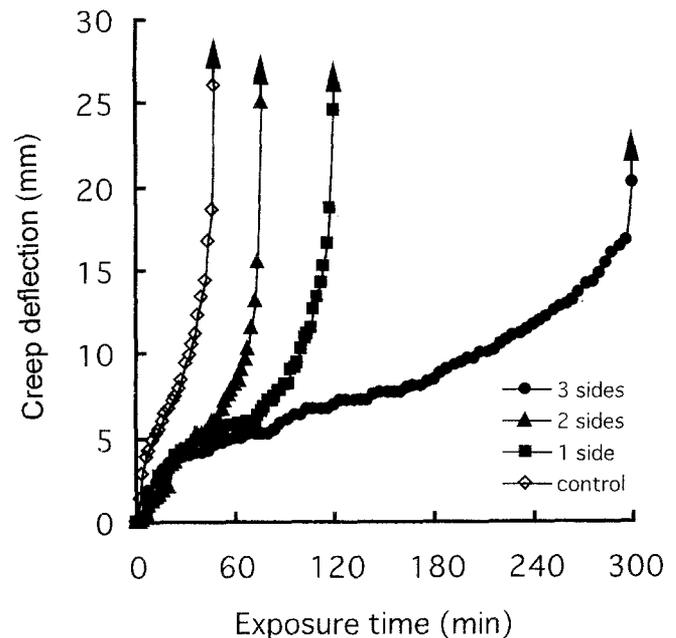


Fig. 2. Relation between exposure time and creep deflection of LVL joint covered with a large sheet of GPS

Table 1. Bending test results

Specimen	Density (g/cm ³)	Maximum load (N)	MOR (MPa)	MOE (×10 ³ MPa)
LVL without joint ^a	0.585 (0.013)	8600 (1200)	67.0 (9.6)	12.0 (0.6)
LVL with a butt joint ^a	0.594 (0.012)	2000 (130)	15.0 (1.1)	4.6 (0.5)
LVL with a butt joint covered with GPS (large, three sides) ^b	0.585 (0.012)	2000 (39)	15.8 (0.2)	4.4 (0.5)

LVL, laminated veneer lumber; GPS, graphite phenolic sphere; MOR, modulus of rupture; MOE, modulus of elasticity

^aValues are the average of 10 specimens; values in parentheses are standard deviations (SD)

^bValues are the average of three specimens

× 39.5 mm) sheet, no significant differences were observed between the three locations, although values were still smaller than those without GPS. From these results it can be said that GPS sheeting protects the surface of a joint directly exposed to fire by preventing rapid deflection.

Effect of GPS sheet on time to rupture

The effect of sheet size on the time to rupture is presented in Fig. 3. The fire resistance, expressed as time to rupture, of the LVL joint was improved by GPS. The times to rupture of all the samples covered with GPS were longer than that of the control (without GPS). Without GPS the time to rupture was about 50 min, whereas with GPS it exceeded 60 min. It should be noted that even the small sheet prolonged the time to rupture of the LVL joint. The longest time to rupture was exhibited by samples covered with a sheet 50 × 158 mm (large) on all three sides of the joint and was more than six times the control value.

Time to rupture increased with the size of the sheet – significantly so when all three sides of the joint were covered. When GPS covered only the sides, however, the increase was slight. This is because in these samples the LVL joint was exposed directly to the fire from underneath. On the other hand, if GPS covered only the bottom of the joint, the effect on time to rupture improved. In summary, the location and size of the GPS sheet have a remarkable effect on the time to rupture of the LVL joint.

Failure of the joints covered with three sides GPS sheets (viewed from underneath) is shown in Fig. 4. Charring was more pronounced in the joints without GPS than with GPS. When the bottom of the joint was covered with a large or medium-size sheet of GPS, it took about 40 min for the flame to penetrate and the char growth plus deflection to split the LVL in two. The GPS remained adherent to the LVL surface until the samples actually split. Therefore, the spread of fire along the length of the sample was prevented,

and consequently the development of char was delayed. When the small sheet was used, it took about 30 min for the GPS layer to peel off due to charring. In the control (without GPS), the fire directly burned the LVL and charring was rapid. The charred area was consequently greater than for the GPS-covered samples.

Temperature rise of the LVL butt joint

Temperature measurements obtained with thermocouples inserted in the center of the joint and between the metal plate connector and LVL are presented in Fig. 5. In the center of the joint, the temperature increased to about 100°C during the first 30 min of exposure to fire in both bottom-covered (left graphs) and uncovered (right graphs) samples. When GPS (large or medium sheet) covered the bottom of the joint, the temperature remained below 200°C for at least 90 min. (The critical temperature at which cellulose starts to degrade is 260°C.) The large sheet of GPS covering three sides prevented the temperature from reaching 260°C throughout the test (until the sample broke). Without GPS sheeting over the bottom of the joint, the temperature rose quickly after 40 min in the completely unprotected joint (control); however, GPS (large or medium-sized sheet) on the sides delayed the temperature rise to 260°C for at least 60 min.

The temperature measured between the metal plate connector and LVL rose faster than that in the center of the joint. A similar trend was observed regardless of whether the bottom of the joint was protected with GPS. With GPS (large or medium size) covering on the bottom, the temperature remained below 260°C for at least 2 h. The large GPS sheet on three sides kept the temperature below 260°C throughout the test. When the bottom of the joint was unprotected, the temperature rose quickly in the control; and for at least 60 min it stayed below 260°C for the two sides with the GPS covering (large or medium size).

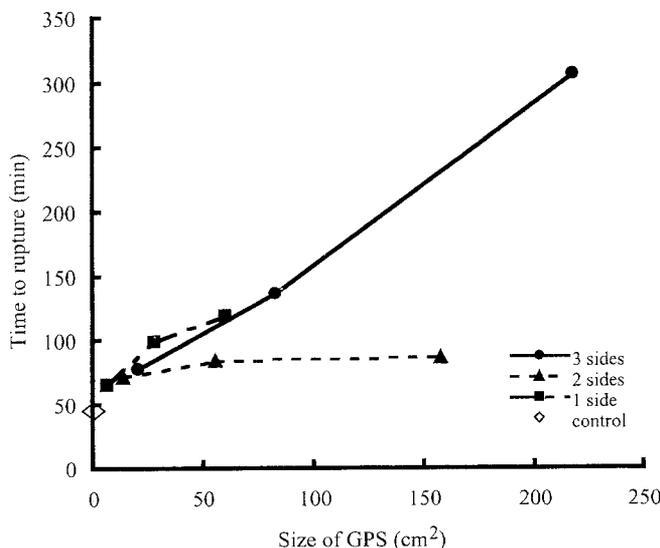


Fig. 3. Effect of the size of the GPS sheet on the time to rupture

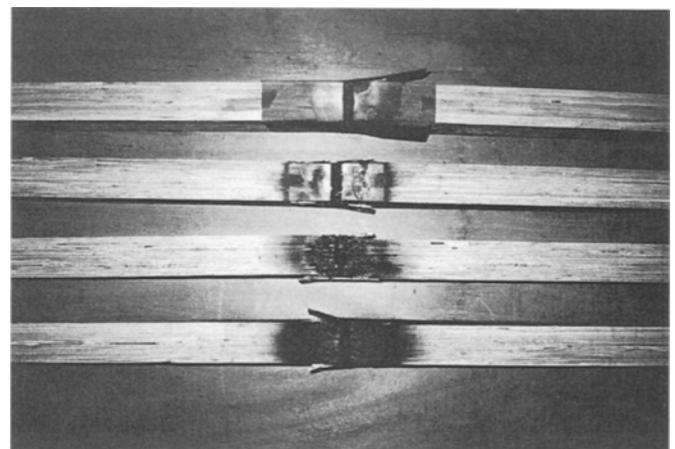
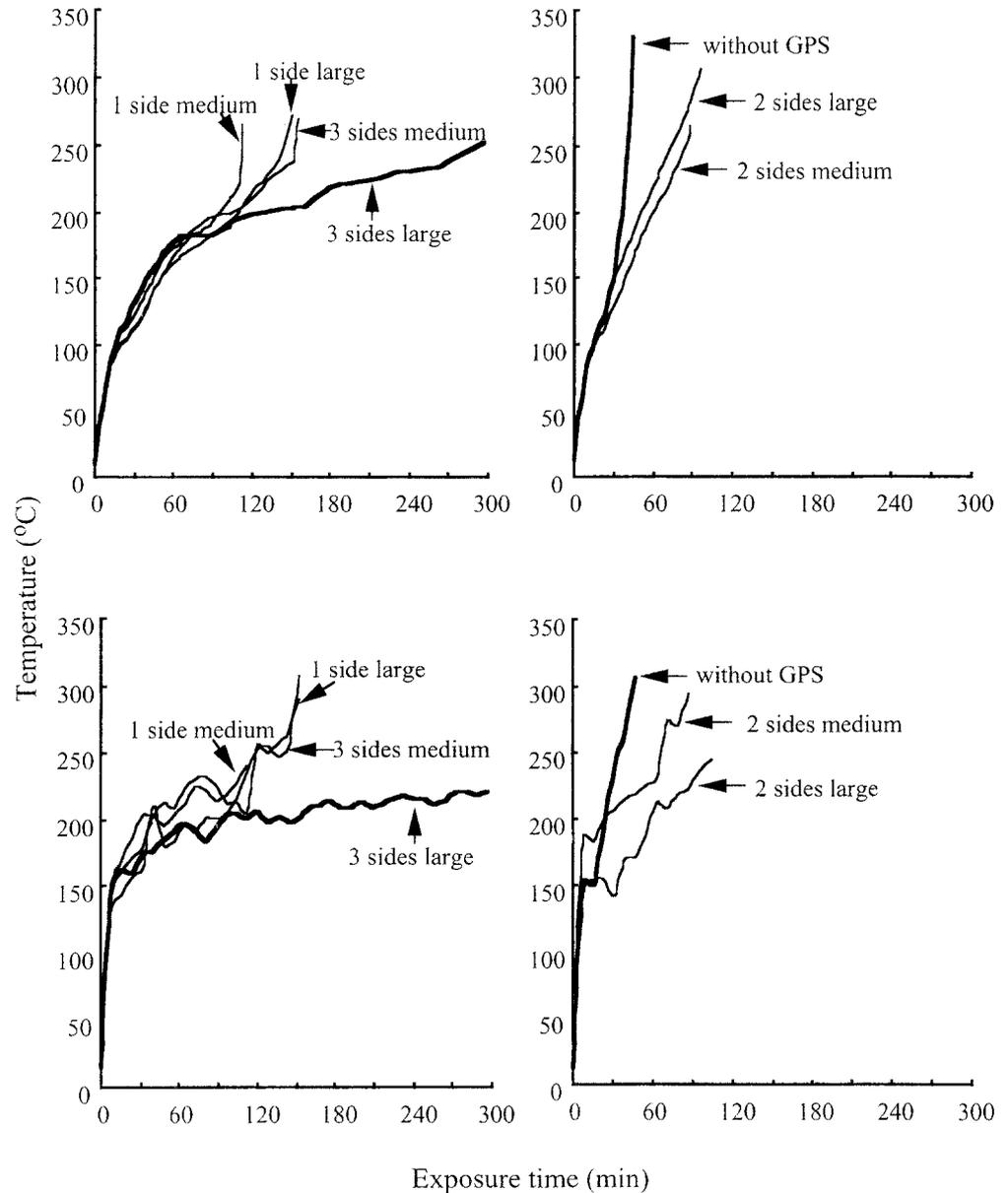


Fig. 4. Typical failures of joints covered with GPS on three sides (view from underneath). Amount of GPS, from the top: large, medium, small, and none

Fig. 5. Temperature rise at the LVL joint during the test is detected by thermocouples. *Upper graphs, At center; lower graphs, between metal plate connector and LVL. Left, Joint covered at bottom. Right, Joint not covered at bottom*



The effect of sheet size on time to reach the critical temperature of 260°C in the center of the joint is shown in Fig. 6. The obvious effect of the size and location of the sheet can be observed. The joint covered on all three sides by a large sheet of GPS exhibited the longest time to reach the temperature, followed by that covered on the bottom only. The joint covered on just the sides showed a shorter time because the bottom was directly exposed to the flame.

Covering the joint with a medium or large sheet prevented the temperature from reaching 260°C for at least 2h. It is thought that when the sample is exposed to fire, heat is distributed throughout the GPS layer before it reaches the LVL. The distribution of heat was much faster in the horizontal (length) than vertical (thickness) direction. Measurement of the thermal properties of the GPS layer showed that the thermal diffusivity in the horizontal direction is 7.5 times that in the vertical direction. Further analysis of thermograph images and the data described below

give a clearer explanation about the heat distribution in the GPS layer.

In summary, the results of measuring temperature rise at the joint showed that the GPS sheeting protects the joint from a rapid increase of temperature. As a result, the fire-retardant properties of the joint were improved.

Thermograph analyses

Thermograph analysis was done to clarify the improvement in the fire properties of the LVL joint covered with GPS by observing the heat transfer and temperature change on the surface of the joint in real time. Several thermograph techniques have been found useful for evaluating the fire-resistant properties of polymer, wood, and wood composites.¹⁴⁻¹⁶ They can be combined with existing fire tests to obtain more information about the process of burning.

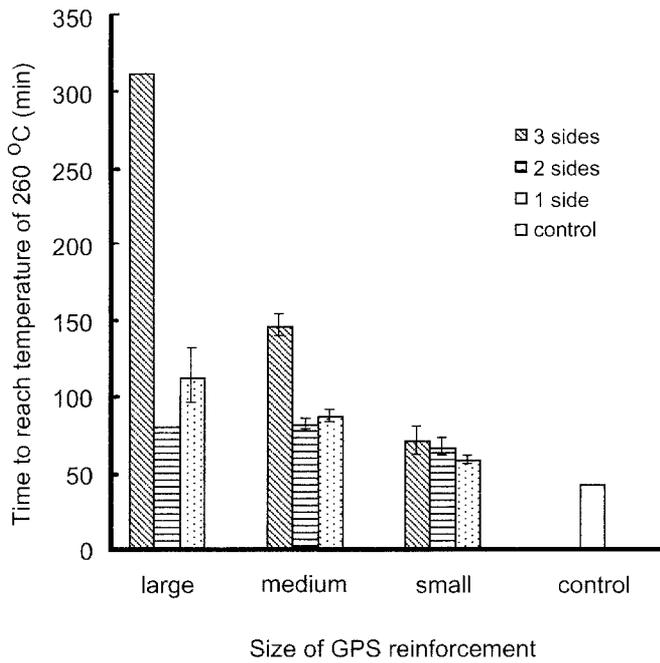


Fig. 6. Effect of the size of the GPS sheet on the time to reach 260°C in the center of the LVL joint detected by a thermocouple. *I*-bars show the standard deviation

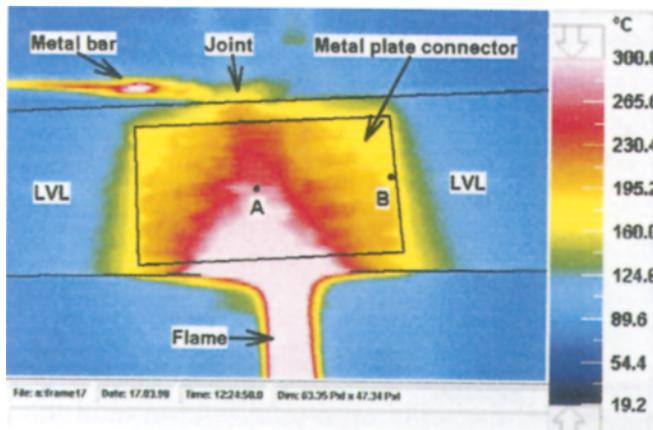


Fig. 7. Thermograph image of LVL joint (side view). A and B are points at the center and edge of the metal plate connector where the temperature difference during the test is calculated

Anisotropy in thermal properties of the GPS sheet, determined using laser flash measurements, and the effect of the sheet in protecting the joint from fire are shown in the thermograph analyses.

Figure 7 shows a typical thermograph image of the side surface of an LVL joint. The analysis is focused on an area of the surface of the metal plate connector (Fig. 7, in the square), and points A and B, which represent the center and edge of the metal plate connector. The temperature in the area or at each point can be obtained using available software. The percentage of area hotter than 260°C on the metal plate connector was calculated throughout the fire test. This area represents the critical part of the joint before

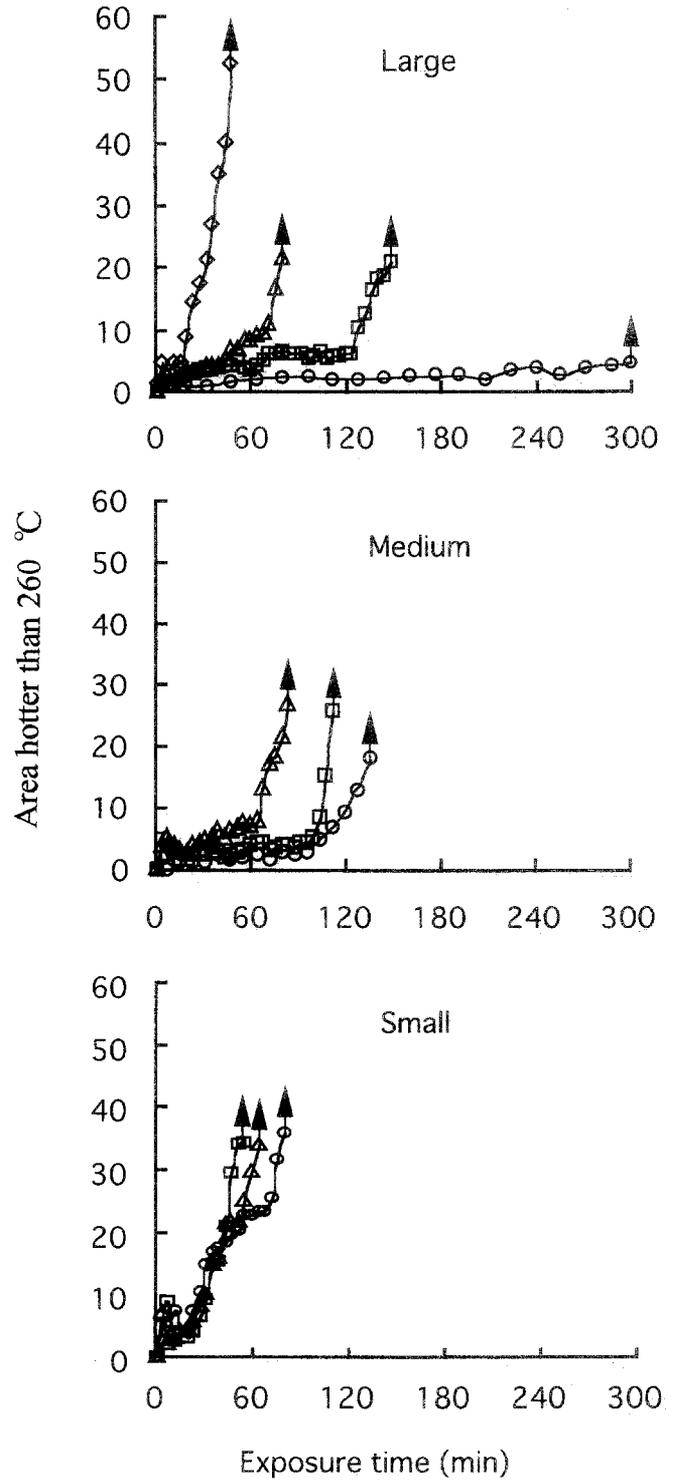


Fig. 8. Percent area hotter than 260°C on the surface of the metal plate connector during the fire test. *Diamonds*, control; *circles*, three sides; *triangles*, two sides; *squares*, one side

rupture. The results for large, medium, and small sheets of GPS are presented in Fig. 8. The size of the covering and the location had a marked effect on the area. With the large sheet, the area was less than 10% when all three sides were covered throughout the test until failure. When the bottom alone or two sides were covered, the value was about 20%.

The uncovered joint, by contrast, broke when the area reached more than 50%. A similar effect of location was seen with the medium-sized GPS covering: The samples broke when the area reached about 20%–30%. For the small GPS covering, however, there was no difference in the effect of location; failure occurred when the area was about 35%.

The results of area analysis (Fig. 8) show the same trend as the data for time to rupture (Fig. 3) and the time to reach 260°C measured by the thermocouples at the center of the joint (Fig. 6). The measurements show that addition of a GPS sheet reduced the area hotter than 260°C, increased the time to rupture, and increased the time to reach a temperature of 260°C. Thus, thermograph analysis may be a good tool with which to assess fire-resistant properties. Further modeling of the fire resistance of LVL joints covered with GPS using thermograph analysis would be useful.

Figure 9 shows thermograph images for all treatments and uncovered (control) GPS LVL joints at 40 min, the time

when the control reached the critical temperature of 260°C. The GPS sheet is considered to function as a heat radiator. When the flame touches the joint covered with GPS on the bottom, the heat radiates through the horizontal surface of the sheet. This observation was confirmed by quantitative measurement of the thermal properties of the GPS sheet using the laser flash method. The measurement revealed that thermal diffusivity is 7.5 times greater in the horizontal direction than vertically, which means that the heat flows faster along the surface than through the sample. Effective protection was achieved when the sheet covered the bottom or all three sides and was of medium or large size. The small GPS sheet was found not to be effective, although it was slightly better than no GPS.

Figure 10 shows the analyses of point temperature at the center and edge of the metal plate connector. Throughout the test, the temperature rises of specimens bottom-covered and uncovered with GPS were compared. The flame was concentrated mainly on the center of the joint, so the temperature rise at the edge was less. When the bottom of

Fig. 9. Thermographs of the surface of the LVL joint at 40 min of fire exposure (when the center of the control joint reached 260°C)

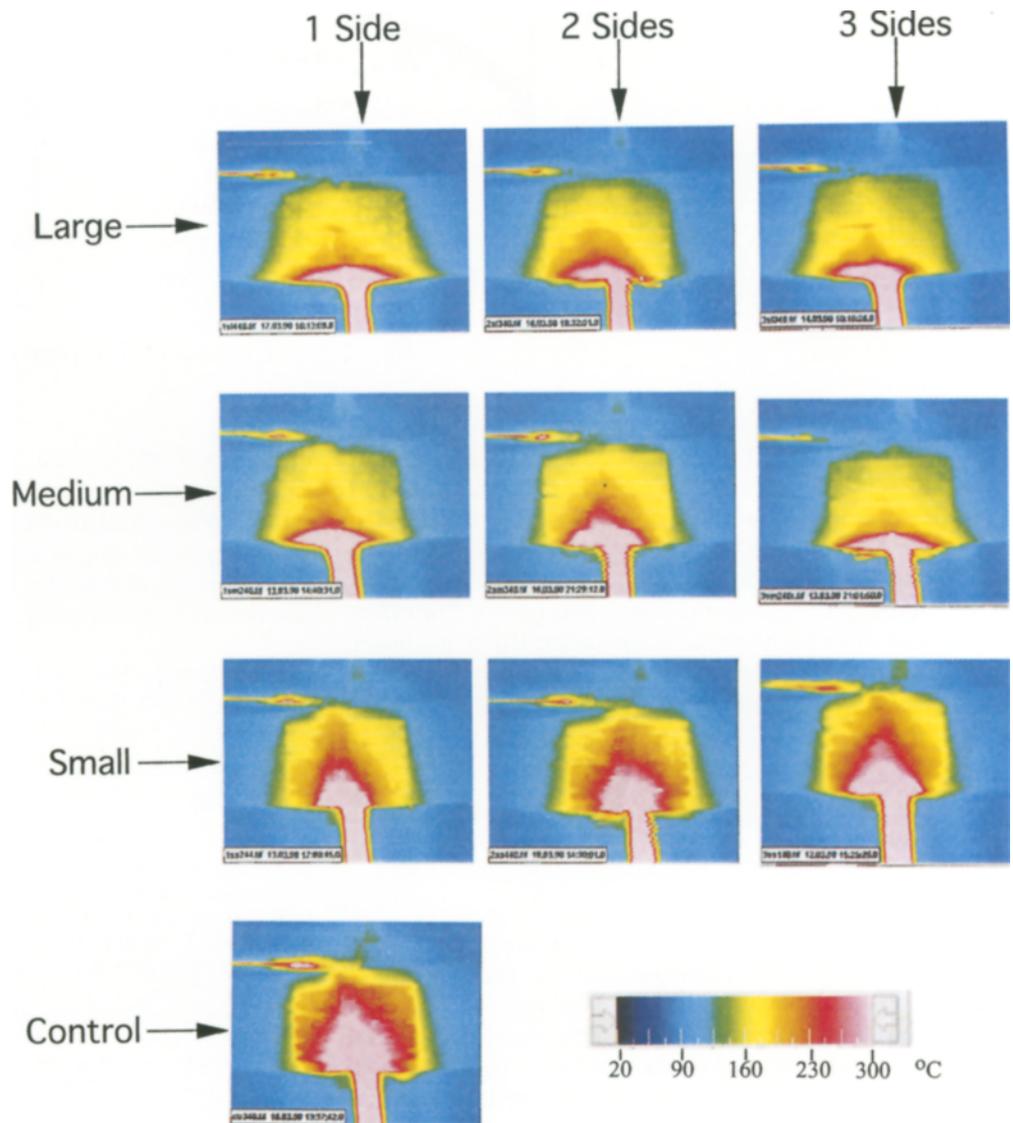
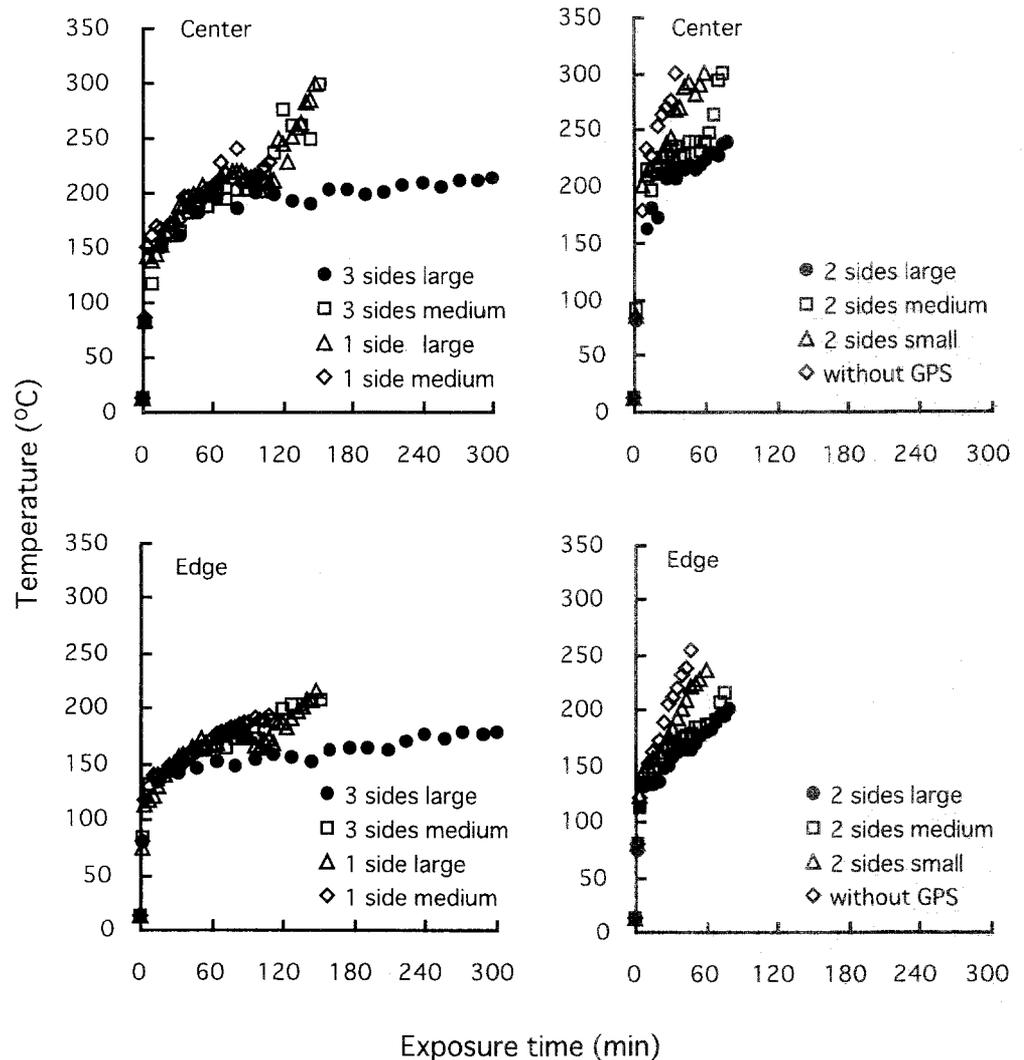


Fig. 10. Temperature at the center and edge of the metal plate connector detected by thermography. *Left graphs*, Bottom side covered with GPS. *Right graphs*, Not covered



the joint was covered with GPS, the temperature rose gradually for the first 2 h. When all three sides were covered it rose constantly, and when only two sides were covered the difference was slight. When the bottom of the joint was not covered with GPS, the temperature rose quickly at both the center and edge, although the center was hotter. The effect of size was still observed, the temperature rise being lower for the large sheets followed by the medium-sized and small sheets. The joint without GPS showed the fastest increase in temperature.

Conclusions

An LVL butt joint made with metal plate connectors was covered with GPS sheeting and tested for creep under fire. The performance was evaluated, and a thermographic analysis was conducted to clarify the results. The fire resistance of the joint was significantly improved by the GPS. The size and location of the sheet had a marked effect on the time to rupture of the joint. To prevent the joint from heating to the critical temperature of 260°C in less than 2 h,

a sheet of GPS at least 35 × 79 mm covering the fire-exposed surface is needed. It is suggested that the GPS sheeting plays a role as a heat radiator and protects the joint from a rapid increase in temperature. The improvement in fire properties due to the GPS sheet was clarified in this experiment using thermograph analyses.

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