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Derivation of shear modulus of the RPF adhesive layer in block shear tests using Digital Image Correlation

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ABSTRACT: In order accurately to evaluate the strength of wood-based materials, it is important to consider not only the physical properties of wood, but also the shear performance of the adhesive layer. In this paper, the digital image correlation (DIC) method was implemented on block shear tests to determine the shear modulus of the adhesive layer and the wood, which is unglued lamina. The specimens were made from three types of softwoods and resorcinol phenol formaldehyde resin adhesive (RPF). Test results showed that the shear modulus of the adhesive layer determined by DIC was almost same as that of the wood. Conversely, the coefficients of variation of the shear modulus were smaller than the elements when Japanese cedar and Japanese larch were glued together.

KEYWORDS: wood-based materials, digital image correlation, block shear test, adhesive layer

1 - INTRODUCTION

The adhesive layer of wood-based materials is a special boundary created as the adhesive cures while penetrating microscopic pores of the wood surface[1)]. This layer is responsible for transmitting stresses acting between the elements, such as laminas, veneers and fibers. Therefore, the mechanical property of the adhesive layer can influence the strength performance of the overall wood-based material. However, since the adhesive layer is much thinner than the elements, it is difficult to measure the strain along the layer using strain gages or other means. In addition, many combinations of elements, adhesives, and adhesive conditions are possible, which complicates the investigation of the effects of these manufacturing factors on the properties of the adhesive layer.

On the other hand, in recent years, developments in optical and image processing technologies made a non-contact strain measurement method called DIC more familiar. This is the method to measure the strain of the entire lateral surface of a specimen coated with a random pattern by continuously photographing the specimen during the test, and comparing the relative changes between the images. By appropriately selecting the image sensor and lens, this method can be used for a variety of test scales, ranging from the analysis of swelling behaviour in wood tissue, micro area, to the measurement of strain distribution in large-section beams, macro area.

Therefore, in this study, by combining DIC and the block shear test, with three wood species as parameters, the relationship between shear strain and stress in the adhesive layer was determined. The shear modulus of the adhesive layer was also derived based on the elastic region of the stress-strain curve. Additionally, by determining the shear properties of the individual elements, the influence of the adhesive on shear performance was analyzed.

2 - BACKGROUND

Before the development of optical measurement techniques, Keylwelth and Höfer[2)] determined the Young's modulus of the adhesive layer by laminating and bonding beech in the radial direction and applying tensile load in the lamination direction. Clad[3)] also measured the displacement of the adhesive layer relative to shear stress by carefully observing the shear surface with a microscope during the tensile shear test. Since the 2000s, non-contact strain measurement methods such as DIC

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and Electronic Speckle Pattern Interferometry (ESPI) have been used to analyze the strain on adhesive layers. Müller and Gindl *et al.* [4)5)] used ESPI to measure the strain on adhesive layers glued with one-component polyurethane adhesive (1C-PUR) and RPF, and reported that the difference in adhesive types affects the shear strain distribution. Wang *et al.* [6)] also used ESPI to analyze the effect of lathe checks in poplar veneer on the shear strain of the adhesive layer. With regard to studies using DIC, Guan *et al.* [7)] examined the effect of the combination of phenol formaldehyde resin adhesive (PF) and sealants to fill lathe checks on the strain distribution of the adhesive layer. Li *et al.* [8)]. analyzed the effect of the spread rate of urea formaldehyde resin adhesive (UF) and PF on the shear strain.

Thus, although previous studies have attempted to determine the mechanical properties of the adhesive layer, it is difficult to say that sufficient knowledge has been obtained considering the combination of elements and adhesives. In addition, most of the previous studies were conducted on hardwoods such as beech and poplar, and there is little knowledge on softwoods used as elements for structural wood-based materials in Japan. Also, few studies have focused on comparing the properties of the adhesive layer with those of the wood. In this study, block shear specimens made of Japanese softwoods were examined by devising a method for their preparation, using not only the wood species but also the presence or absence of an adhesive layer as parameters.

3 - PROJECT DESCRIPTION

In this study, block shear specimens were initially prepared using RPF adhesive. Parameters were wood species and the presence or absence of an adhesive layer. Next, block shear tests and strain measurements were conducted by DIC. Finally, the physical properties of the RPF adhesive alone used in this study were obtained to examine its effect on shear strength and shear modulus.

4 - EXPERIMENTAL SETUP

4.1. Materials

Table 1 summarizes the specifications of specimens and Fig. 1 shows the preparation method. The experimental parameters are the wood species and the presence or absence of the adhesive layer. Laminas of Japanese cedar (*Cryptomeria japonica*), Japanese cypress (*Chamaecyparis obtusa*) and Japanese larch (*Larix kaempferi*), each of them 400 mm length, 120 mm width and 35 mm thickness, were prepared for this study. The

Table. 1 Specifications of specimens

Series	Wood species	Adhesive layer	Number of specimens	Density[kg/m^3]	M.C.[%]
Cedar-N	Japanese cedar	None	12	373(10.9)	12.7(4.4)
Cedar-A		One layer	12	368(8.7)	13.0(3.9)
Cypress-N	Japanese cypress	None	11	447(10.6)	13.7(5.5)
Cypress-A		One layer	12	443(9.9)	13.8(5.3)
Larch-N	Japanese larch	None	12	471(9.6)	10.2(6.2)
Larch-A		One layer	12	475(9.9)	10.2(2.8)

coefficient of variation is noted in parentheses

Table. 2 Adhesive conditions

Wood species	Spread rate[g/m^2]	Pressure[MPa]	Pressing time[h]
Japanese cedar	250	0.7	24
Japanese cypress		1.0	
Japanese larch			

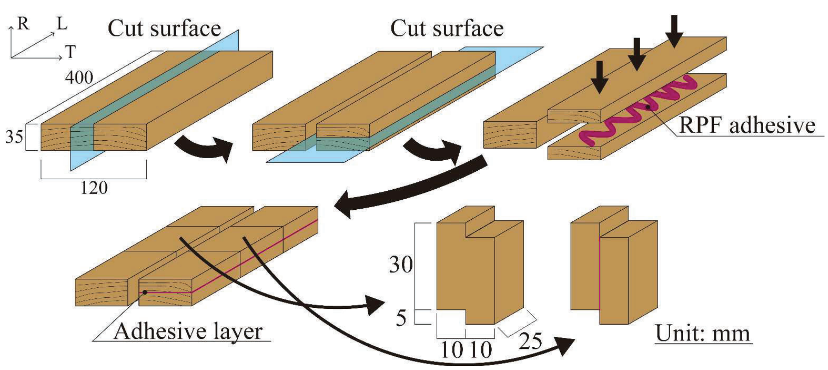

Fig. 1 Specimens preparation method

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specimens without the adhesive layer were cut directly from the lamina to form block shear specimens, while the specimens with the adhesive layer had the shear surface coinciding with the adhesive layer. For all series, the number of specimens was set to 12. However, one Cypress-N specimen was excluded due to failure to measure load values during the test, resulting in a total of 11 specimens. Moisture content (M.C.) was measured by the oven-drying method after the test.

The preparation method of the specimens was as follows. Firstly, the laminas were divided into two parts along radial (LR) plane and cured in a chamber (65 % RH and 20 ℃) for over a week. Next, one of the split laminas was divided along the tangential (LT) plane. After dividing, each cut LT plane was planed, and the cut surfaces were glued to each other using RPF adhesive (Oshika Co. Ltd., main agent: D-4320, hardening agent: DL-880). The adhesive conditions are given in Table 2. Following the adhesive operation, laminas were cured in the chamber again for more than a week. Finally, block shear specimens were machined from each lamina with and without the adhesive layer, so that longitudinal direction positions were the same.

4.2. Methods

The setup for the block shear test is shown in Fig. 2. A universal testing machine (MinebeaMitsumi Inc., TGJ-50kN) was used for tests. A compression load was given monotonically and the test speed was 0.5 mm/min. The loading force was applied until the specimen failed in shear. All tests were conducted under air-dried conditions. Shear strength τ_{max} was calculated by dividing the maximum load P_{max} by nominal shear area A as shown in Eq. (1).

$$\tau_{max} = P_{max} / A \quad (1)$$

Strain distribution at the LR plane was measured by DIC. One side-face of each specimen was sprayed with black paint (Kampe Hapio Co. Ltd., Ales Arch, color: mat black) following previous research[9]. The sprayed face was photographed at intervals of 1 Hz using a CMOS camera (Allied Vision Technologies Co. Ltd., Alvium 1800 U-1236) and a lens (Kowa Optronics Co. Ltd., LM1119TC) during the shear test. The photography area was approximately 20.8 mm width and 28.4 mm height, with the center of photography area and specimen matched. The lens magnification ratio was 0.5x. At this time, a length of one side of a pixel was equal to 6.9 µm. During the photography process, lighting was applied to illuminate the surface in order to ensure sufficient luminance.

Fig. 3 shows the procedure for deriving the shear modulus. First, shear strain distribution on the DIC analysis area (Fig. 2) was measured. Vic 2D (Correlated Solutions Co. Ltd.) was used for the analysis. The subset size for DIC analysis was 35 pixels and the distance between subsets was 10 pixels. Second, the load and shear strain distribution along the shear plane at the time when each image was taken were extracted. Finally, the nominal shear stress (τ) and the average shear strain (γ) were obtained, and the slope of the linear region of the τ-γ curve was determined as the shear modulus of the

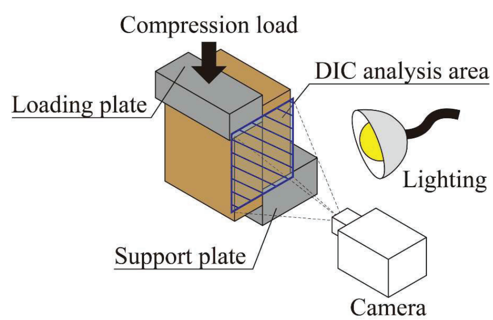

Fig. 2 Setup for the block shear test and strain measurement by DIC

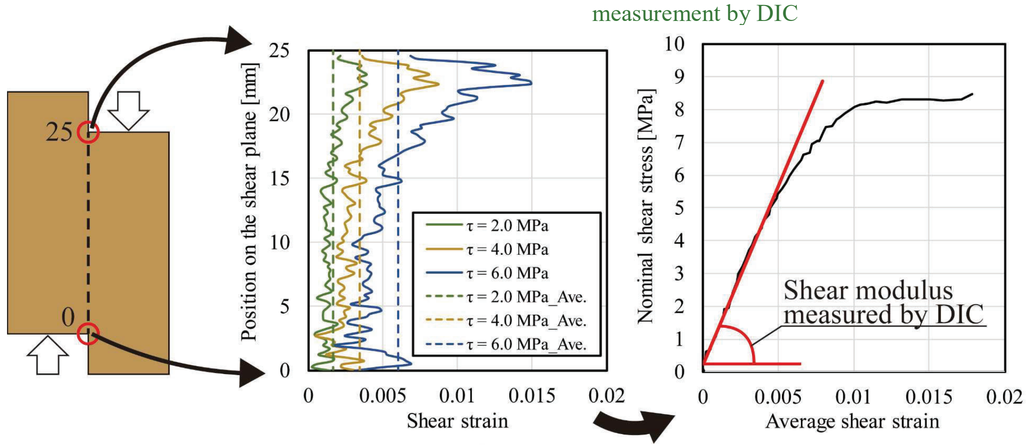

Fig. 3 Derivation of shear modulus using DIC

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adhesive layer (for the glued series) or the wood (for the unglued series).

After the block shear test, to obtain the mechanical properties of only RPF, a compression specimen was created from the same adhesive used for preparing the block shear specimens. First, the main agent and hardener were mixed and poured into three polypropylene containers, 80 g into each container. The specimens were then cured at room temperature for about six months. After curing, compression specimens were cut out, and two-axis strain gauges (Tokyo Measuring Instruments Laboratory Co. Ltd., FCA-10-11) were attached to both sides.

The test setup is shown in Fig. 4 and the dimensions and weight of RPF specimens are given in Table 3. The load was applied at a rate of 0.5 mm/min, continuing until the specimen yielded. Axial strain was measured in the compression direction, while transverse strain was measured in the perpendicular direction. From the obtained nominal compressive stress, axial and transverse strains, the Young's modulus (E) and Poisson's ratio (ν) in the elastic region were determined. Finally, assuming that the RPF is isotropic, the shear modulus (G) was calculated using Eq. (2).

$$G = E / 2(1+\nu) \tag{2}$$

5 - RESULTS AND DISCUSION

Fig. 5 shows the shear strength of each series. The block shear specimens taken next to each other (glued and unglued) were connected with solid line. Welch's two-tailed t-test for τ_{max} was conducted for each wood species; no significant difference between glued and unglued was found. On the other hand, the average shear strength of the bonded series tended to be lower for both species, although no statistically significant differences were observed. This may be due to fiber breakage at the shear surface.

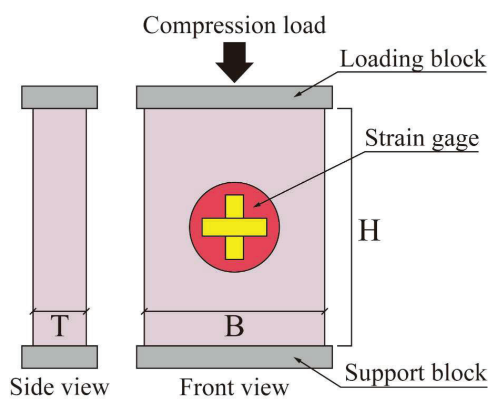

Fig. 4 Setup for the compression test of RPF specimens

Table 3 Dimensions and weight of the RPF specimens

Series	H[mm]	B[mm]	T[mm]	W[g]	ρ [kg/m^3]
RPF-1	36.9	28.4	11.9	15.4	1237
RPF-2	37.0	23.1	11.4	12.5	1281
RPF-3	34.0	29.5	11.6	15.1	1298

Fig. 6 shows the shear modulus determined by DIC for each specimen and their average value. Welch's t-test was conducted for each series and there was no significant difference between glued and unglued. Conversely, the coefficients of variation (C.V.) for Cedar-A and Larch-A were smaller than those for Cedar-N and Larch-N, respectively. For Japanese cypress, C.V. between Cypress-A and Cypress-N were almost the same.

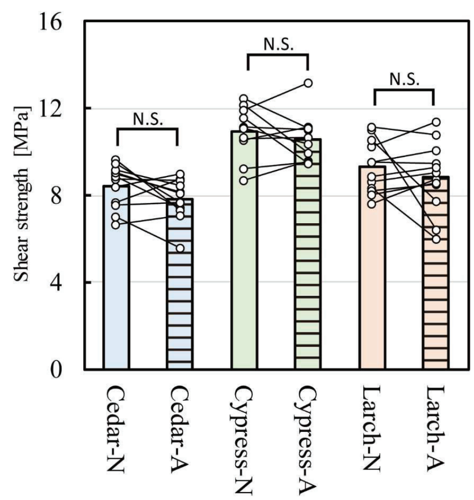

Fig. 5 Shear strength of each series
Note: Plots indicate the experimental values and bar charts indicate the mean values.

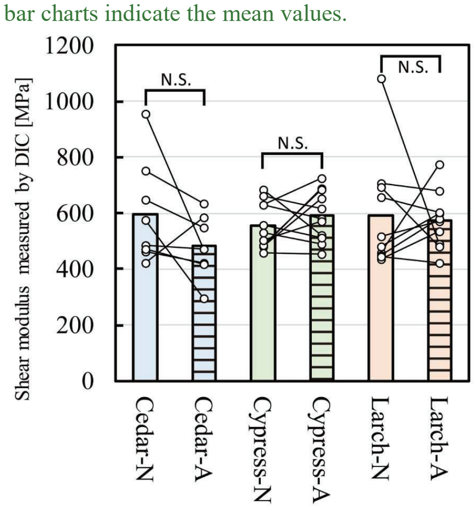

Fig. 6 Shear modulus of the adhesive layer or the wood determined by DIC
Note: Plots indicate the experimental values and bar charts indicate the mean values.

There was no significant difference in the shear modulus of glued and unglued specimens. One possible reason for this phenomenon is that the shear modulus of RPF adhesive may be similar to that of wood. Therefore, only the RPF adhesive was cured and then subjected to the compression test to determine the shear modulus.

Fig. 7 shows the relationship between nominal compressive stress and axial strain and transverse strain of RPF. All three specimens yielded at nearly 50 MPa and Young's modulus values were obtained from the slope of the stress-axial strain relationship in the elastic region.

Fig. 8 shows the relationship between the ratio of transverse to longitudinal strain, or Poisson's ratio, and nominal compressive stress. Poisson's ratio did not remain constant in the early stage of force application (about 0 to 10 MPa). This is considered to be due to the deformation of the small voids within the RPF specimen collapsing, which resulted in minimal transverse strain. Additionally, as the stress approached the yield point, Poisson's ratio began to increase again. Therefore, Poisson's ratio was referenced only to the range of compressive stresses from 20 to 40 MPa, and the mean value of this interval was calculated as Poisson's ratio for each specimen.

Table 4 shows the mechanical properties of RPF specimens. It should be noted, however, that the RPF specimens in this study have a larger volume than the actual adhesive layer and their curing process is different, e.g., it is not under pressure. Therefore, different physical properties may be obtained in other test methods. The shear modulus (G) of the RPF obtained from the compression test was slightly higher than that of the wood or adhesive layer. The coefficient of variation (C.V.) was 6.2 %, which was smaller than the values for the wood and adhesive layer obtained from the DIC (min: 14.9 % for Cypress-N, max: 34.3 % for Larch-N).

The reason why there was no significant difference in shear modulus between the glued and unglued series is considered to be because the G of the RPF is on the same order as that of the wood. On the other hand, the reason for the smaller C.V. for Japanese cedar and Japanese larch can be attributed to the fact that the C.V. of the RPF adhesive was smaller than that of the wood, resulting in a more homogeneous boundary.

6 - CONCLUSION

In this study, the block shear tests and shear strain measurements by DIC were conducted. As a result, there was no significant effect of the RPF adhesive to increase the shear strength and the shear modulus than the wood when softwood was glued. These may be due to the fact that the fibers are cut off at the shear surface of glued series and G of the RPF is not significantly larger than wood. Although no specific effect due to the adhesive layer was observed in this study, it suggests that the reinforcement effect may be significant when RPF

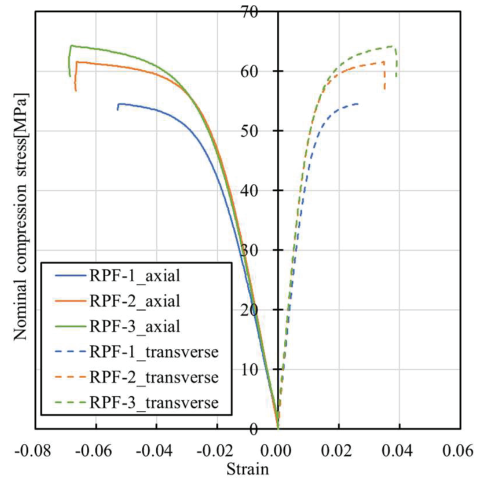

Fig. 7 Relationship between nominal compressive stress and axial strain, transverse strain

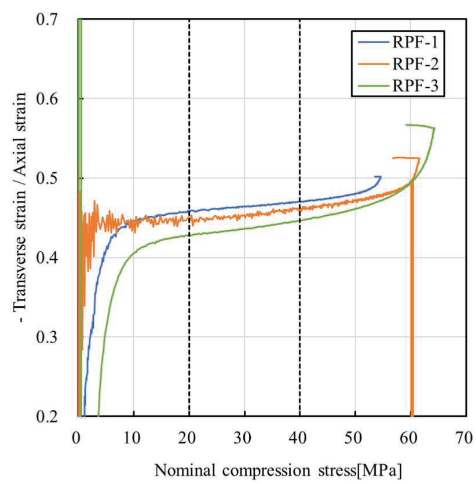

Fig. 8 Relationship between Poisson's ratio and nominal compressive stress
Note: Poisson's ratio was calculated from the interval between the dotted lines.

Table 4 Mechanical property of RPF specimens

Series	E [MPa]	v	G [MPa]
RPF-1	2370	0.46	809
RPF-2	2663	0.45	916
RPF-3	2514	0.44	875
mean	2516	0.45	867
C.V.[%]	5.8	3.1	6.2

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adhesives are used to bond wood species which have lower shear strength and shear modulus. Additionally, a variety of adhesives for wood, such as Water-based Polymer Isocyanate adhesive (WPI, API) and Polyurethane adhesive (PUR), are used alongside RPF. Therefore, we plan to conduct future experiments with different adhesives, in order to study the effect of adhesive type on the shear performance of the adhesive layer.

7 - ACKNOWLEDGMENT

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