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Simultaneous determination of shear strength and shear modulus in glued-laminated timber using a full-scale shear block specimen

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Abstract A newly developed full-scale shear block specimen was used to simultaneously determine the shear strength and shear modulus of glued-laminated timber. The shear modulus was calculated using the shear strain distribution measured by means of digital image correlation. To obtain the exact relationship between shear modulus and shear strength, the shear strain in the intended shear plane was measured. A relatively high correlation coefficient of 0.75 was found between the shear modulus and nominal shear strength in two types of glued-laminated timber tested: sugi (*Cryptomeria japonica*) and Douglas-fir (*Pseudotsuga menziesii*). Good correlation was also found between the density of middle lamina and shear strength. However, the relationships to density showed species dependence, which was not observed in the relationship between shear modulus and shear strength.

Key words Full-scale shear block specimen · Digital image correlation · Shear modulus · Shear strength · Glued-laminated timber

Introduction

In the production of glued-laminated timber, laminae with high stiffness are placed on the outside and laminae with lower stiffness are placed near the neutral plane. This arrangement is intended to give high stiffness, as well as high modulus of rupture, in bending. In short deep beams, however, the shear strength of the laminae near the neutral plane becomes critical and should also be taken into account.

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Shear strength, however, shows a strong size effect, and the relationship between shear area and shear strength has been investigated.[1–3] Ido et al.[3] conducted a full-scale shear block test (shear area, 100 × 100 mm) to obtain the shear strength of Japanese construction-size timber. They confirmed that the shear strength of full-scale specimens was 27% lower than that obtained with the small, clear shear block specimens (shear area, 30 × 30 mm) specified in the Japanese Industrial Standards (JIS).

In practice, it is convenient to estimate the shear strength from the shear modulus, just as the modulus of rupture is estimated from the modulus of elasticity. In most cases, however, only the shear strength is measured, and the basic relationship between shear modulus and shear strength has not been sufficiently investigated. Müller et al.[4] and Sretenovic et al.[5] measured shear strength and shear modulus using a modified edgewise shear test similar to the American Society for Testing and Materials (ASTM) D 1037. They found a high correlation between shear strength, density, and shear modulus. Divos et al.[6] used a vibration technique to measure the shear modulus in construction-size timber. They also conducted screw withdrawal resistance tests to investigate the relationship between shear strength and shear modulus and found a high correlation between screw withdrawal resistance and shear modulus. Our previous study[7] proposed a new method for measuring shear modulus of a small, clear shear block specimen using a digital image correlation (DIC) technique. The shear modulus measured with shear block specimens was compared with that obtained from torsion tests, and good agreement was found. This new method is suitable for obtaining the relationship between shear strength and shear modulus, because it can measure the exact shear modulus of the intended shear plane.

The objective of the present study was to assess the applicability of the proposed method to full-scale specimens. The relationship between shear strength and shear modulus was evaluated in glued-laminated timber fabricated from sugi (Japanese cedar, *Cryptomeria japonica*) and Douglas-fir (*Pseudotsuga menziesii*).

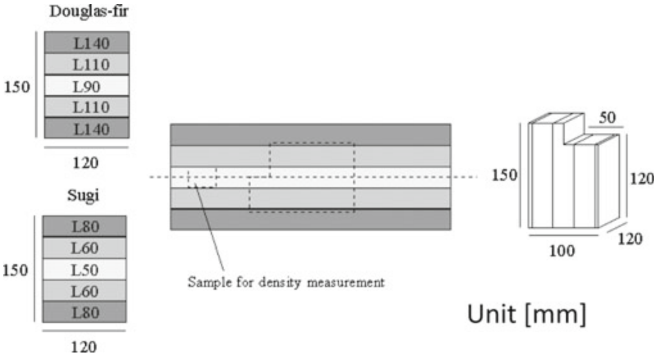

Fig. 1. Layout and dimensions of the full-scale shear block. L, Grade of lamina. The figure that follows the "L" denotes the criterion value of modulus of elasticity (MOE) in 10^{-1} GPa

Materials and methods

Specimen preparation

Full-scale shear block specimens were cut from five-ply glued-laminated timber. Figure 1 illustrates the dimensions and the orientation of the shear block specimen. One shear block sample was cut from one glued-laminated beam. The shear plane of each shear block specimen was adjusted to the center of the timber to test the shear strength of the middle lamina. The outer laminae were trimmed to reduce the width of the shear block specimen to 100 mm. Two different types of glued-laminated timber were prepared: one was composed of laminae made from sugi and the other from Douglas-fir. The laminae were graded based on their modulus of elasticity in bending. The grades of laminae were determined according to the Japanese Agricultural Standard specified for glued-laminated timber. A total of 15 samples of each type were tested. Moisture content was measured after tests using an oven-dry method. The mean moisture content was 11% ± 0.4%.

Full-scale shear block testing[3]

The testing apparatus was composed of four movable parts: a vertical sliding block, a loading block, an upper fixture plate, and a lower adjustable stage (Fig. 2). The loading block was attached to the vertical sliding unit via a cylinder, which enabled rotation around the x-axis (see Fig. 2). The upper part of a specimen was secured with the fixture plate to prevent rigid body rotation. The lower support was adjusted to create a 5-mm offset in the vertical plane between the edges of the loading block and the stage. Testing was conducted on a compression testing machine (MAEKAWA; capacity 3000 kN) in accordance with JIS Z2101.

Strain measurement using digital image correlation technique[8]

Images of both sides of a shear block specimen were taken simultaneously using two digital cameras connected to each other through the operation of an electrical switch. Image size was 2000 × 3008 pixels, with the longer edge aligned with the grain direction of the specimens. Image resolution was 0.052 mm/pixel. The digital image correlation technique requires that the specimen surface patterns have sufficient contrast and be randomly distributed. The surface of Japanese cedar or Douglas-fir in their natural form cannot provide this. Thus, before testing, black ink was sprayed onto the surface of specimens to generate randomly distributed patterns. Figure 3 shows an example of the acquired images. The loads at the acquisition of images were recorded to relate the measured strain to the nominal stress. Images were then analyzed using the DIC program[8] to obtain the distribution of strain.

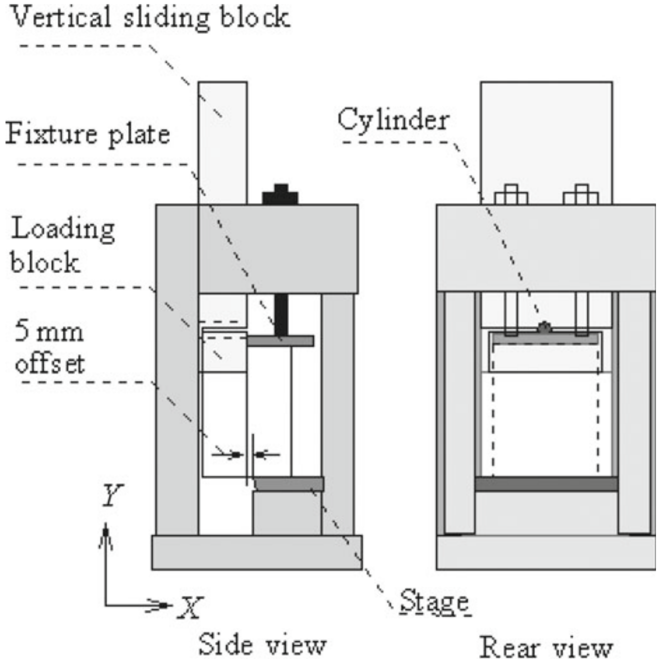

Fig. 2. Schematics of the loading apparatus

Results and discussion

Strain distribution

To confirm that adequate shear force was introduced to the intended shear plane, the plane of maximum or minimum shear strain was investigated. The angle that defines the plane of maximum or minimum shear strain was computed as follows.

Transformation of shear strain from the x–y coordinate system to the new x'–y' coordinate system is calculated by the following equation[9]:

$$\gamma_{x'y'} = -(\varepsilon_x - \varepsilon_y)\sin 2\theta + \gamma_{xy}\cos 2\theta \qquad (1)$$

where ε_x and ε_y are the normal strain in the x and y direction, respectively; γ_{xy} is the shear strain; and θ is the angle that defines the x'–y' coordinate system (see Fig. 3).

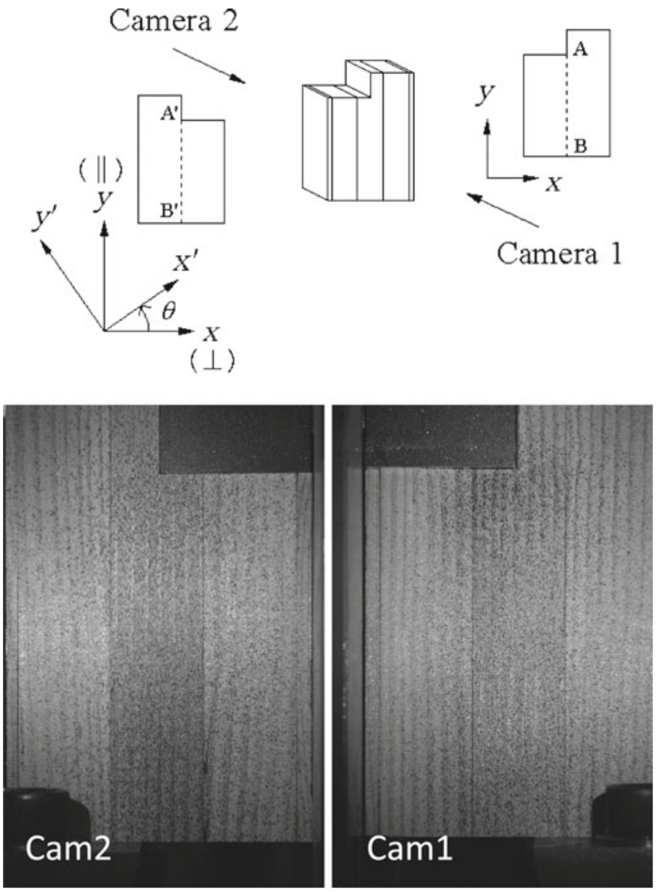

Fig. 3. Definition of the coordinates and examples of acquired images. ∥, Parallel to the grain direction; ⊥, perpendicular to the grain direction. *Cam2*, Camera 2; *Cam1*, camera 1

To find the plane of maximum/minimum shear strain, Eq. 1 is differentiated with respect to θ and the derivative set equal to zero:

$$\frac{d\gamma_{x'y'}}{d\theta} = -2(\varepsilon_x - \varepsilon_y)\cos 2\theta - 2\gamma_{xy}\sin 2\theta = 0 \tag{2}$$

Hence,

$$\tan 2\theta = -\frac{(\varepsilon_x - \varepsilon_y)}{\gamma_{xy}} \tag{3}$$

An example of the calculated angle θ, designating the plane of maximum/minimum shear strain at 51% of the maximum load, is shown in Fig. 4. As the shear strain on mutually perpendicular planes is numerically equal, the plane of maximum/minimum shear strain was selected to form the smallest angle with the y-axis. The mean value of the angle on each side of all specimens was 83° (see Fig. 3, Camera 1) and 99° (see Fig. 3, Camera 2), respectively. It can be concluded that adequate shear force is introduced in the intended plane.

The distribution of shear strain and perpendicular to the grain at maximum load is shown in Fig. 5 and Fig. 6, respectively. The shear strain was largest near the re-entrant corner and gradually decreased toward the lower end of the specimen. As for the maximum shear strain and

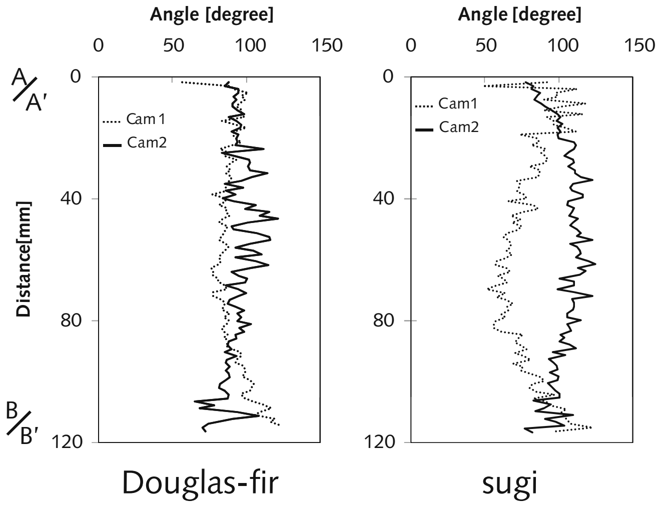

Fig. 4. Distribution of angles defining the plane of maximum or minimum shear strain at 51% of maximum load. Distribution was measured along lines AB and A′B′ (see Fig. 3). Angles were calculated according to Eq. 3. The definition of angle is shown in Fig. 3

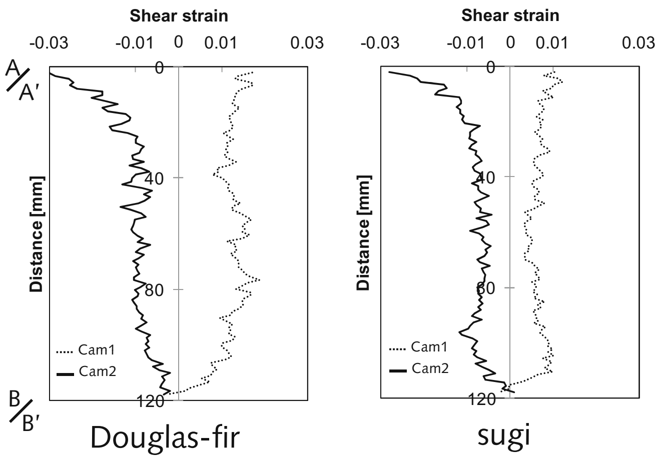

Fig. 5. Shear strain distribution along lines AB and A′B′ at the maximum load. (See Fig. 3 for position of lines AB and A′B′)

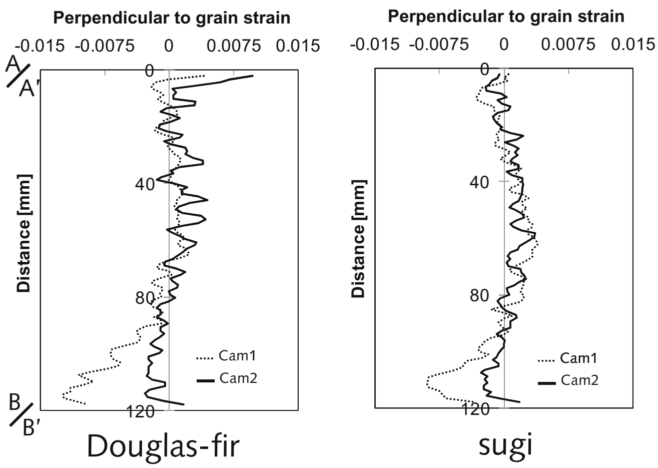

Fig. 6. Distribution of perpendicular to grain strain along lines AB and A′B′ at the maximum load. (See Fig. 3 for position of lines AB and A′B′)

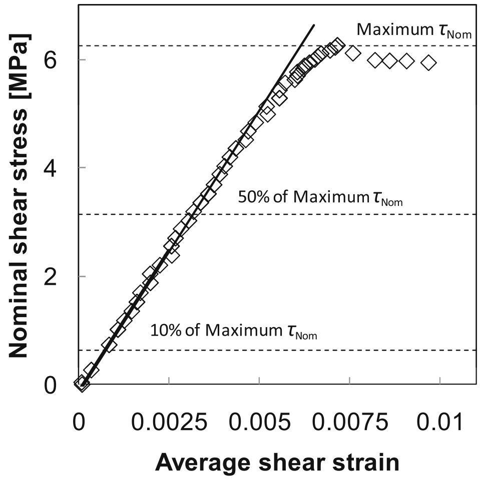

Fig. 7. Relationship between nominal shear stress (τ_{Nom}) and average shear strain

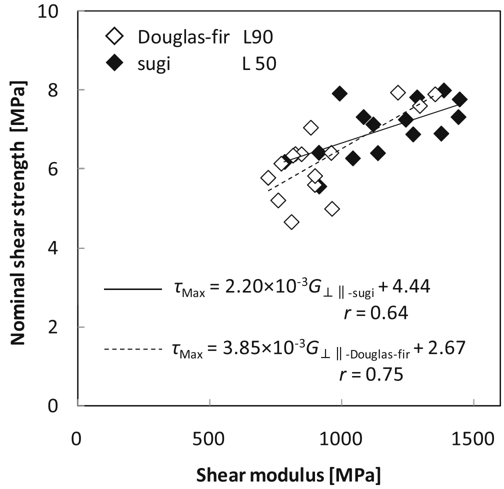

Fig. 8. Nominal shear strength plotted against shear modulus. τ_{Max}, Nominal shear strength; $G_{\perp\parallel}$, shear modulus; r, coefficient of correlation

total shear strain, bias between sides of a specimen was observed.

As seen in Fig. 6, strain perpendicular to the grain was present in the entire shear plane. Hence, pure shear conditions were not achieved in this test. In general, the upper part of the shear plane was subjected to tension perpendicular to the grain and the lower part was subjected to compression perpendicular to the grain. However, there was also localization of large tensile strain depending on the growth ring structure (earlywood or latewood). In the sugi example shown in Fig. 6, localization of perpendicular to the grain tensile strain was off the intended shear plane.

Determination of the shear modulus

The nominal shear stress is computed as

$$\tau_{Nom} = \frac{P}{A} \tag{4}$$

where τ_{Nom} is the nominal shear stress, P is the load, and A is the shear area. In the standard test of JIS and ASTM, shear strength is defined as the maximum nominal shear stress.

In the linear elastic range, the nominal shear stress and the average shear strain along the intended shear plane may satisfy the following relationship:

$$\tau_{Nom} = G_{\perp\parallel}\gamma_{AV} \tag{5}$$

Where, $G_{\perp\parallel}$ is the shear modulus and γ_{AV} is the average shear strain. For calculating the average shear strain, strain over an area of 1.1 mm in the x direction and 117 mm in the y direction was integrated, and averaged for both sides of a specimen. The size of the area was determined to have a geometrically similar relationship to the area used in our previous study[7] for small, clear shear block specimens specified in JIS Z2101.

An example of the relationship between average shear strain and nominal shear stress is shown in Fig. 7. The shear modulus was calculated as the gradient of a straight line that was fitted to the linear elastic part of the relationship curve. The fitted range was chosen between 10% and 50% of the maximum nominal shear stress.

Table 1. Summary of the test results

	Sugi			Douglas-fir		
	Mean	SD	CV (%)	Mean	SD	CV (%)
ρ [kg/m^3]	396	39	10	453	60	13
$G_{\perp\parallel}$ [MPa]	1162	209	18	934	196	21
τ_{Max} [MPa]	7.00	0.72	10	6.26	1.01	16

ρ, oven-dry density; $G_{\perp\parallel}$, shear modulus; τ_{Max}, shear strength; SD, standard deviation; CV, coefficient of variation

Relationship between shear modulus and shear strength

Nominal shear strength and shear modulus are listed in Table 1. Although the grade of lamina was higher in Douglas-fir, the shear modulus and shear strength were lower compared to sugi. When used as a beam member, the middle lamina is usually subjected to the maximum shear stress. The results here suggest that additional checking of the shear properties is desirable when determining the composition of glued-laminated timber.

The relationship between nominal shear strength and the shear modulus is shown in Fig. 8. A good correlation was found for both types of glued-laminated timber. When the results of both species were mixed, a correlation coefficient (r) of 0.75 was obtained. This result was in good agreement with the results by Divos et al.,[6] who found a correlation coefficient of 0.80 between shear modulus and shear strength in construction-size timber. Furthermore, the linear regression explanation for sugi ($\tau = 2.20 \times 10^{-3}\ G_{\perp\parallel\text{-sugi}} + 4.44$; $r = 0.64$), was comparable to the previous measurement of the same species using JIS standard shear block specimens[7] ($\tau_{RL} = 2.01 \times 10^{-3}\ G_{RL} + 4.08$; $r = 0.50$).

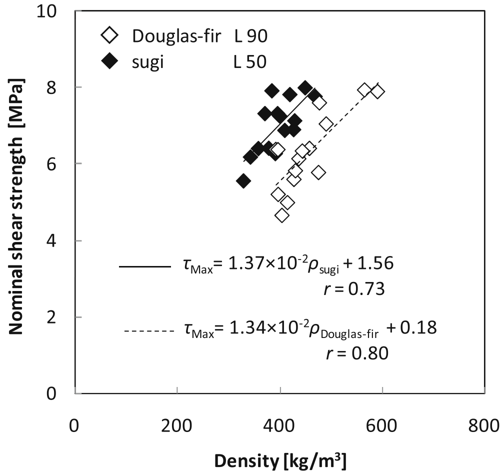

Fig. 9. Nominal shear strength plotted against density. τ_{Max}, Nominal shear strength; ρ, oven-dry density; r, coefficient of correlation

As described in the previous section, a bias was observed for the total shear strain on each side of a specimen. When the shear modulus was calculated using only the strain value of the more deformed side, the correlation coefficient between shear strength and shear modulus increased to 0.80. In contrast, when only the strain value of the less deformed side was used, the correlation coefficient decreased to 0.40. This provisional calculation suggests that the nominal shear strength may be dominated by partial rather than entire shear deformation.

Relationship between shear strength and density of middle lamina

A good correlation was also found between density and shear strength. Figure 9 shows the relationship between the oven-dry density of middle lamina and the shear strength. To measure the density of middle laminae, samples were cut from the vicinity of full-scale specimens (see Fig. 1). Within a single species, the oven-dry density and the shear strength showed a good linear relationship. However, the relationship was species dependent; when the results of both species were mixed, the correlation coefficient decreased to 0.41.

Conclusions

The strain distribution of full-scale shear block specimens was examined to obtain shear modulus and shear strength simultaneously. Strain distribution was measured using a digital image correlation method. Shear modulus was calculated from the nominal shear stress, and shear strain was measured in the intended shear plane.

A relatively high correlation coefficient of 0.75 was obtained from the relationship between calculated shear modulus and nominal shear strength. A good correlation was also found between the density of middle lamina and the shear strength. However, the relationship showed species dependence. The method presented here can be used to determine the basic relationship between shear modulus and shear strength in construction-size timber.

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