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Applicability of the Iosipescu shear test on the measurement of the shear properties of wood

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Abstract We examined the applicability of the Iosipescu shear test for measuring the shear properties of wood. Quarter-sawn board of sitka spruce (*Picea sitchensis* Carr.) and shioji (Japanese ash, *Fraxinus spaethiana* Lingelsh.) were used for the specimens. Iosipescu shear tests were conducted with two types of specimen whose longitudinal and radial directions coincided with the loading direction. The shear modulus, yield shear stress, and shear strength were obtained and were compared with those obtained by the torsion tests of rectangular bars. The results are summarized as follows: (1) The Iosipescu shear test is effective in measuring the shear modulus and the yield shear stress. (2) To measure the shear strength properly by the Iosipescu shear test, the configuration of specimen and the supporting condition should be examined in more in detail.

Key words Iosipescu shear test · Shear modulus · Yield shear stress · Shear strength

Introduction

There are many methods for obtaining the shear properties of materials. The torsion test and the 45° off-axis tension or compression test are the most popular methods.[1,2] Using these methods, we can obtain the shear modulus properly. Nevertheless, it is difficult to discuss the validity of the shear stress/shear strain relation in the plastic region using the shear moduli obtained by these methods. In a previous paper, we proposed an equation for predicting the shear stress/shear strain relation from the torsion test result.[3] The torsion test, however, is not a direct method for obtaining the shear stress/shear strain relation in the plastic region. In the 45° off-axis test, the normal stress components always occur in the material as does the shear stress, and it is difficult to obtain the pure shear stress/shear strain condition. Thus, we believe that it is difficult to obtain the yield stress and shear strength by these methods.

As for wood, the shear test method is standardized by the Japan Industrial Standard (JIS) as in JIS Z-2101. It is widely known that the shear properties obtained by this method are apparent because the uniform shear stress condition cannot be expected in the specimen, and that the real shear properties cannot be obtained by this method. Despite this drawback, the standard JIS shear test has been conventionally undertaken to measure the shear strength of wood. On various occasions we need to obtain the pure shear properties of wood properly. From this viewpoint, however, the conventional JIS test is insufficient. Therefore, we believe that a shear test method that can evaluate the real shear properties of wood should be standardized as quickly as possible.

In 1967 Iosipescu proposed an in-plane shear testing method for metal with a double-notched beam shape.[4] Since then, his method has been widely applied to measurement of the shear stress/shear strain relation of such materials as fiber-reinforced plastics (FRP). Recently, the Iosipescu shear test has been thought to be a promising method because a uniform shear stress condition can be attained for the specimen under an in-plane condition. We believe that the Iosipescu shear test is promising for wood, although there are few reports on applying the Iosipescu shear test to the measurement of the shear properties of wood.[5] In the present study we measured the shear modulus, shear yield stress, and shear strength of wood and examined the applicability of the Iosipescu shear test for wood.

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Theory

Figure 1 diagrams the Iosipescu shear test specimen. The x- and y-axes are defined as those parallel and perpendicular, respectively, to the long axis of the specimen. When the specimen is loaded asymmetrically as in Fig. 1a, an almost uniform shear stress condition is thought to be obtained at the midlength of the specimen except in the region near the notches. With this loading condition the shearing force equals P in the middle section of the specimen (Fig. 1b), whereas the bending moment is equal to zero in the same section (Fig. 1c). The validity of this hypothesis has been variously examined by finite element analyses.[6–8]

As stated, the shearing force P applies on the region between the notches. Thus, the shear modulus G_{xy} can be measured by obtaining the following equation:

$$G_{xy} = \frac{\Delta P}{td\Delta\gamma_{xy}} \quad (1)$$

where t is the thickness of the specimen, d is the distance between the notches, and γ_{xy} is the engineering shear strain at the midpoint of the notches.

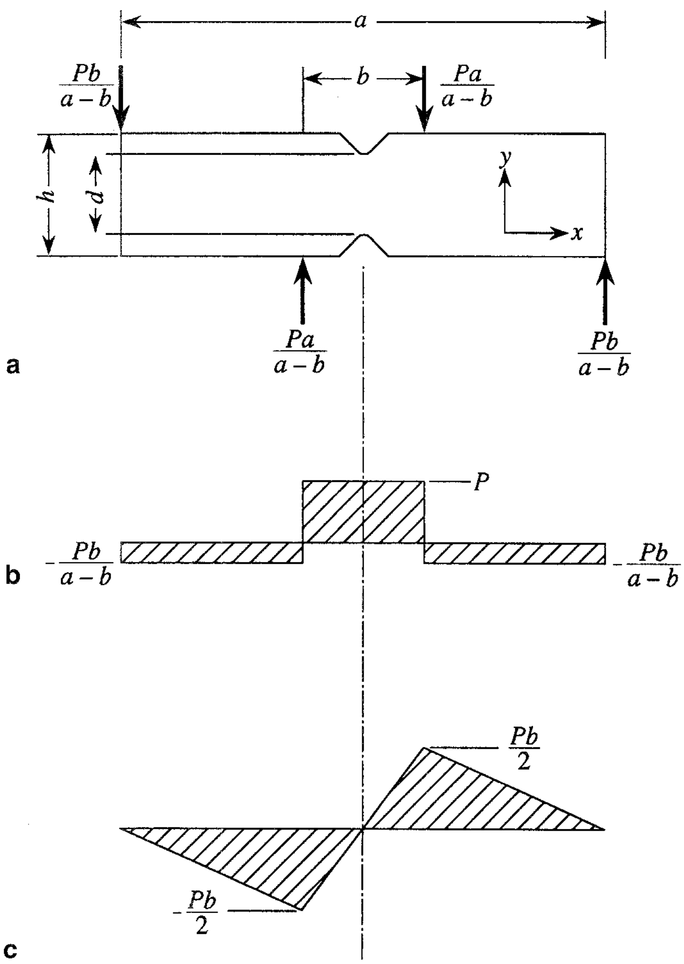

Fig. 1. **a** Applied force, **b** shearing force, and **c** bending moment diagrams for Iosipescu shear specimen

Shear yield stress, Y_{xy}, and shear strength, F_{xy}, are given, respectively, as follows:

$$Y_{xy} = \frac{P_y}{td} \quad (2)$$

and

$$F_{xy} = \frac{P_f}{td} \quad (3)$$

where P_y and P_f are the vertical loads at the occurrence of yielding and failure, respectively.

Experiment

Materials

Sitka spruce (*Picea sitchensis* Carr.) and shioji (Japanese ash, *Fraxinus spaethiana* Lingelsh.) were used for the specimens. The density of spruce was 0.43 g/cm^3, whereas that of shioji was 0.59 g/cm^3. Specimens were conditioned at 20°C and 65% relative humidity (RH) before and during the tests.

Iosipescu shear tests

The Iosipescu shear testing method is standardized for FRP in the American Society for Testing Materials (ASTM) D-5379. However, it is difficult to fabricate the specimen in accordance with the standard because the specimen size defined in the standard is small. Hence, we determined the dimensions of the specimen as Fig. 2. The shape of the specimen is approximately proportional to that of ASTM standard.

Here, we measured the shear properties on the longitudinal-radial (LR) plane, and two types of specimens were prepared. In one type, the radial direction coincided with the long axis of the specimen, whereas the longitudinal direction coincided with it in the other one. We defined these types as "RL-specimen" and "LR-specimen," respectively.

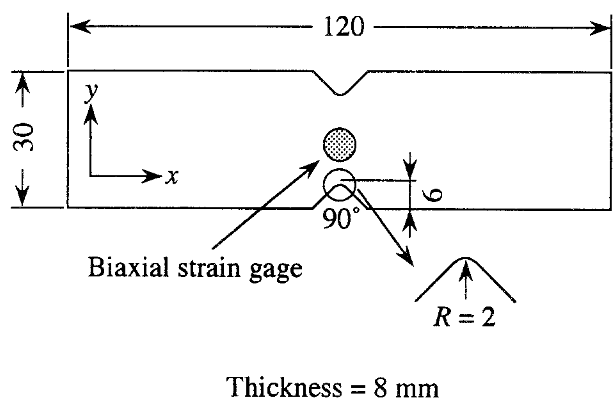

Fig. 2. Iosipescu shear test specimen (units: millimeters)

To measure the strain condition between the opposed notches, triaxial-strain gauges (gauge length 2mm; YFRA-2-11, Tokyo Sokki Co., Tokyo) were bonded on the opposite surfaces at the midpoint between the notches. Figure 3 shows the triaxial-gauge arrangement. The shear strain γ_{xy} was obtained from the following equation

$$\gamma_{xy} = 2\varepsilon_{\mathrm{III}} - \varepsilon_{\mathrm{I}} - \varepsilon_{\mathrm{II}} \tag{4}$$

where ε_{I}, $\varepsilon_{\mathrm{II}}$, and $\varepsilon_{\mathrm{III}}$ are the strains in the directions of axes I, II, and III, respectively, shown in Fig. 3.

Figure 4 diagrams the test fixture, which was the same type developed at the University of Idaho (named "Idaho fixture"),[9] and the setting of the specimen. As in Fig. 4, the loading surfaces began at points 22 and 12mm away from the center of the test specimen. The vertical load of 1 mm/min loading velocity was applied to the specimen, and the load-strain relations were recorded by a XY-recorder. The shear modulus was obtained from the initial linear segment of shear stress/shear strain curve. The plastic shear strain component, γ^{P}_{xy}, was then separated by the following equation:

$$\gamma^{\mathrm{P}}_{xy} = \gamma_{xy} - \frac{\tau_{xy}}{G_{xy}} \tag{5}$$

where τ_{xy} is the shear stress. The shear stress/plastic shear strain relationship was formulated by Ludwik's power function represented as follows[10]:

$$\tau_{xy} = Y_{xy} + a\left(\gamma^{\mathrm{P}}_{xy}\right)^{n} \tag{6}$$

where a and n are the parameters. The yield shear stress Y_{xy} was calculated as that where $\gamma^{\mathrm{P}}_{xy} = 0$. The shear strength was determined by substituting the maximum load into P_{f} of Eq. (3).

The shear modulus, yield shear stress, and shear strength obtained from the RL-specimen are denoted as G_{RL}, Y_{RL}, and F_{RL}, respectively, whereas those obtained from the LR-specimen are as G_{LR}, Y_{LR}, and F_{LR}, respectively. Eight specimens were used for one test condition.

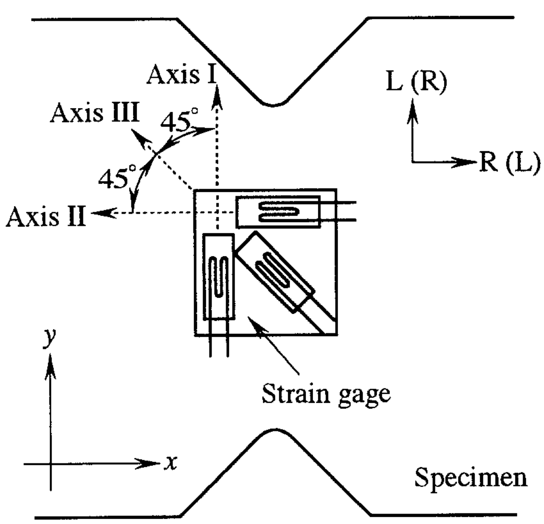

Fig. 3. Triaxial strain gauge arrangement. L, R, longitudinal and radial directions, respectively

Torsion tests

Independently of the Iosipescu shear tests, torsion tests were conducted to measure the shear modulus and yield shear stress. The obtained values were compared with those derived by the Iosipescu shear tests.

Figure 5 shows the shape of the torsion test specimen. To measure the strains at the centers of the side surfaces, the same strain gauges used in the Iosipescu shear tests were bonded on the LR and LT planes. The specimen was twisted by a manual torsion-test device, and the torsional moment/strains relations were obtained. The strain components were transformed into the shear strain by Eq. (4), and the shear moduli on the LR and LT planes were calculated by the following equations.[3]

$$\begin{cases} G_{\mathrm{LR}} = \dfrac{k_{\mathrm{LR}}}{a^2 bk} \cdot \left[-\dfrac{8}{\pi^2}\sqrt{\dfrac{G_{\mathrm{LR}}}{G_{\mathrm{LT}}}} \displaystyle\sum_{n=1}^{\infty} \dfrac{(-1)^{n-1}}{(2n-1)^2} \cdot \tanh \dfrac{(2n-1)\pi b}{2a}\sqrt{\dfrac{G_{\mathrm{LR}}}{G_{\mathrm{LT}}}} \right] \\ G_{\mathrm{LT}} = \dfrac{k_{\mathrm{LT}}}{a^2 bk} \cdot \left[1 - \dfrac{8}{\pi^2} \displaystyle\sum_{n=1}^{\infty} \dfrac{1}{(2n-1)^2} \cdot \left\{ \cosh \dfrac{(2n-1)\pi b}{2a}\sqrt{\dfrac{G_{\mathrm{LR}}}{G_{\mathrm{LT}}}} \right\}^{-1} \right] \end{cases} \tag{7}$$

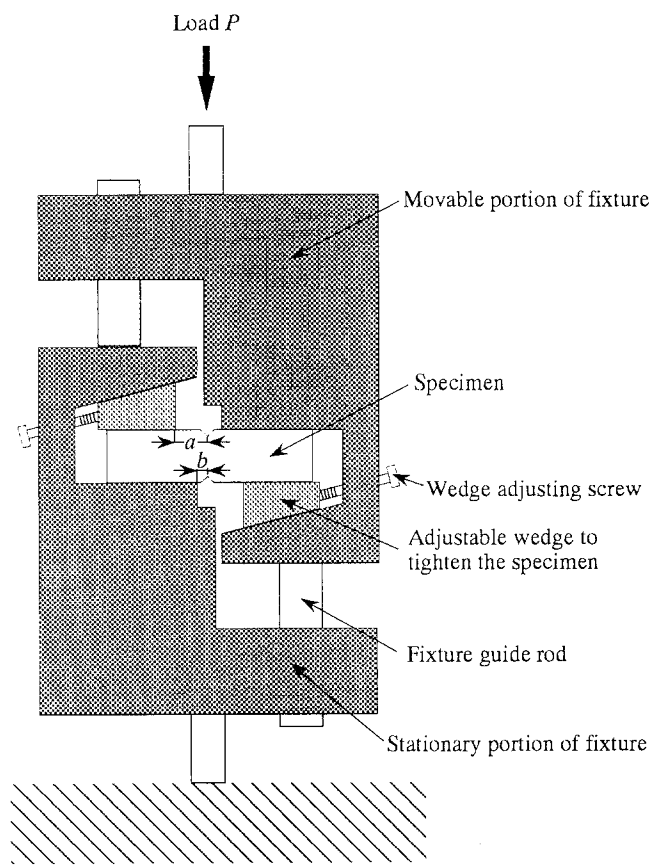

Fig. 4. Iosipescu shear test fixture. *a*, 22 mm; *b*, 12 mm

where a and b are the lengths in the radial and tangential directions, respectively; k_{LR} and k_{LT} are the initial inclination of the torsional moment/shear strains on the LR and LT planes relations, respectively; and k is

$$k = \frac{1}{3} - \frac{2a}{b}\sqrt{\frac{G_{LT}}{G_{LR}}}\left(\frac{2}{\pi}\right)^5 \sum_{n=1}^{\infty} \frac{1}{(2n-1)^5} \cdot \tanh\frac{(2n-1)\pi b}{2a}\sqrt{\frac{G_{LR}}{G_{LT}}} \quad (8)$$

Yield shear stress, Y_{LR}, was calculated by the following equation:

$$Y_{LR} = \frac{M_y}{a^2 bk} \cdot \left[-\frac{8}{\pi^2}\sqrt{\frac{G_{LR}}{G_{LT}}} \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{(2n-1)^2} \cdot \tanh\frac{(2n-1)\pi b}{2a}\sqrt{\frac{G_{LR}}{G_{LT}}} \right] \quad (9)$$

where M_y is the torsional moment at the occurrence of yielding. The value of M_y was determined by formulating the torsional moment/plastic shear strain relation on the LR plane into the Ludwik's power function similar to Eq. (6).

On the other hand, the shear strength cannot be predicted by the torsion test without considering the shear stress/shear strain relation, which cannot be obtained directly by the torsion test. Hence, we thought that the validity of the shear strength predicted by the torsion test should be examined in detail. The comparison of the shear stress/shear strain relations and the shear strengths obtained from the Iosipescu and torsion tests will be mentioned in a succeeding paper.

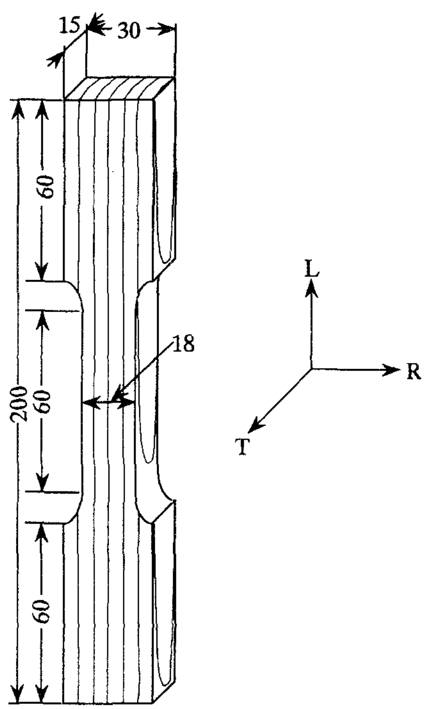

Fig. 5. Torsion test specimen (units: millimeters). *T*, tangential direction

Results and discussion

Figure 6 shows the typical pattens of the shear stress/shear strain relations obtained from the Iosipescu shear tests. The shear stress/shear strain behaviors obtained from the two specimens were similar before the occurrence of failure in the RL specimen. The failure occurred suddenly in the RL-specimen, whereas it occurred rather gradually in the LR-specimen.

Table 1 shows the shear moduli obtained from the Iosipescu shear tests and the torsion tests. The values of shear moduli were similar for the two specimens and coincided with those obtained by the torsion tests.

The yield shear stress obtained from the Iosipescu shear tests and the torsion tests are shown in Table 2. The yield stresses obtained by the RL- and LR-specimens of the Iosipescu shear tests coincided with each other, but these values were smaller than those attained by the torsion tests.

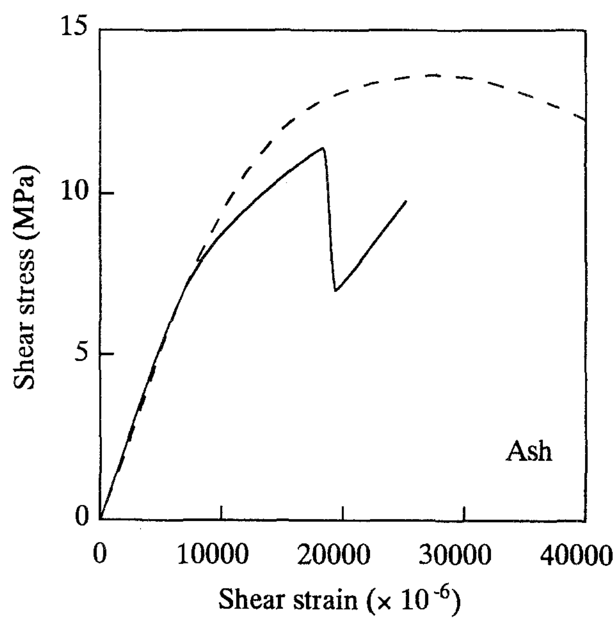

Fig. 6. Typical patterns of the shear stress/shear strain relations obtained from the Iosipescu shear tests. *Solid* and *dashed lines* were obtained from the shear tests of RL and LR specimens, respectively

Table 1. Shear moduli obtained by the Iosipescu shear tests and torsion tests

Species	Iosipescu (GPa)		Torsion: G_{LR} (GPa)
	G_{RL}	G_{LR}	
Spruce	1.09 ± 0.21	1.04 ± 0.38	0.95 ± 0.14
Ash	0.90 ± 0.17	1.05 ± 0.13	1.03 ± 0.11

Results are averages ± SD

In a previous paper, we pointed out that the yield stress determined by the torsion test tends to be about 30% larger than the real value.[11] Considering this phenomenon, we thought that the yield shear stresses were measured appropriately by the Iosipescu shear tests.

Figure 7 shows the typical patterns of the principal strain angle ϕ during the loading process in the Iosipescu shear test. The value of ϕ is calculated from the following equation.[12]

$$\phi = \frac{1}{2}\tan^{-1}\left(\frac{\gamma_{xy}}{\varepsilon_{I} - \varepsilon_{II}}\right) \tag{10}$$

When the pure shear stress condition, ϕ should be 45°. From the finite element calculations by Kumosa and Hull, the principal stress angle deviates from 45° when the specimen has a large orthotropy.[8] From the experimental results, however, the principal strain angle was about 45° for both types. Hence, the pure shear stress condition occurs in the region where the strain gauges were bonded. Thus, we thought that the Iosipescu shear test effectively measures the shear modulus and yield shear stress.

Table 3 shows the shear strengths obtained from the RL- and LR-specimens. This table shows that the shear strength of the RL-specimen, F_{RL} was smaller than that of the LR-specimen, F_{LR}. Figure 6 also indicates this phenomenon. The fractures in the RL-specimen were initiated at the opposed points of the longer supporting edges because of the maximum tensile stresses, which can be predicted by the bending moment diagram shown as in Fig. 1c; and they propagated along the grain, as shown in Fig. 8a. The load reached its maximum at this fracture initiation before the catastrophic failure occurred between the notch. Hence, the values of F_{RL} shown in Table 3 are not regarded as the shear strengths. Even if the shape of the RL-specimen is modified, fractures would be initiated at the notch roots, where the pure shear stress condition cannot be expected, and would propagate along the grain immediately. Therefore, we believe that the shear strength cannot be measured properly using the RL-specimen type. On the other hand, the fracture in the LR-specimen started at the notch roots, as in Fig. 8b, and catastrophic failure occurred between the notches, as in Fig. 8c, by the continuous loading after fracture initiation. The value of F_{LR} was higher than that usually obtained by the JIS shear test.[13] According to Adams and Walrath's results obtained from testing graphite/epoxy composite, the initial fracture does not alter the stress profiles significantly, and the shear stress is thought to be uniform even when the

Table 2. Yield shear stresses obtained by the Iosipescu shear tests and torsion tests

Species	Iosipescu (GPa)		Torsion: Y_{LR} (GPa)
	Y_{RL}	Y_{LR}	
Spruce	6.5 ± 1.6	6.2 ± 1.4	8.7 ± 2.1
Ash	7.5 ± 0.9	7.8 ± 2.1	9.9 ± 1.2

Results are averages ± SD

Table 3. Failure stresses obtained by Iosipescu shear tests

Species	F_{RL} (MPa)	F_{LR} (MPa)
Spruce	7.5 ± 1.4	10.3 ± 1.6
Ash	9.6 ± 0.8	13.7 ± 1.2

Results are averages ± SD

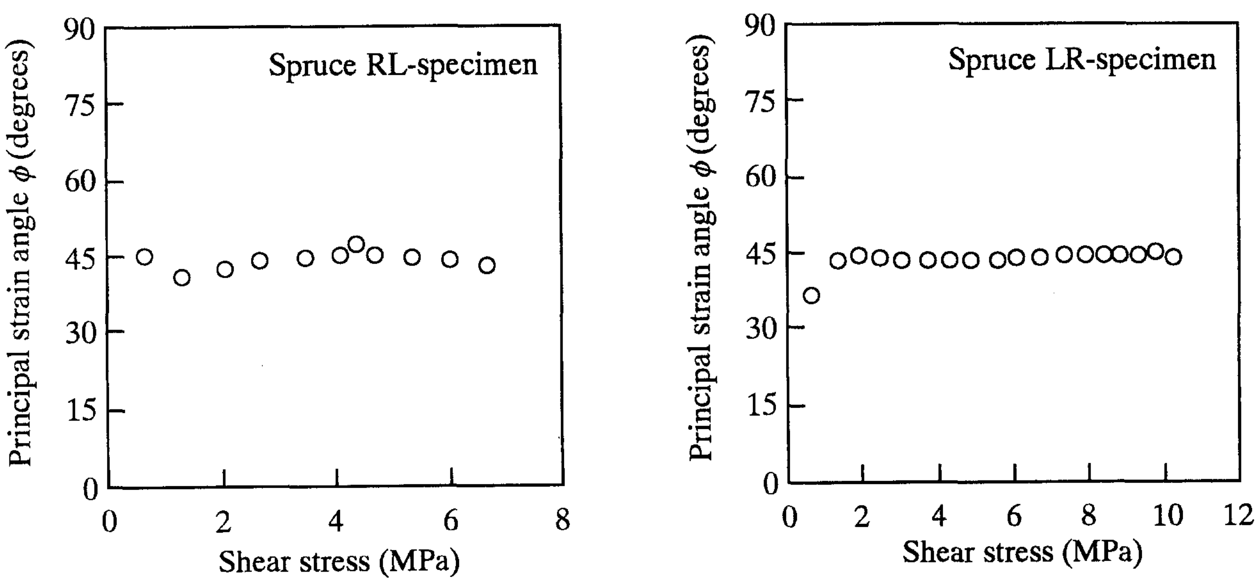

Fig. 7. Variation of the principal strain angle during loading

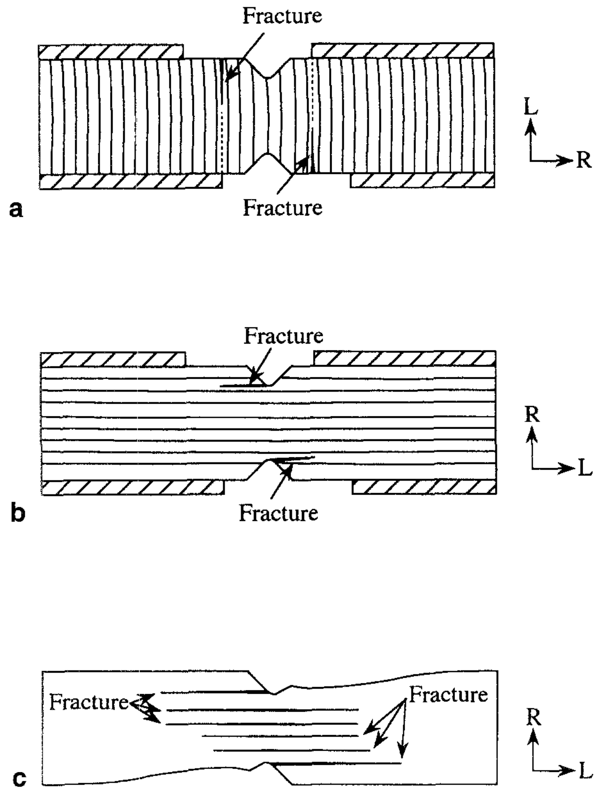

Fig. 8a–c. Fracturing pattern of each type of specimen. **a** RL specimen, fracture initiation; **b** LR specimen, fracture initiation; **c** LR specimen, after unload. *Hatched zones* represent the supports of the specimen

fracture exists.[6] Nevertheless, the RL-specimens tested here deformed seriously, as in Fig. 8c. Despite the pure shear stress condition in the gauge region as in Fig. 6, we are afraid that this large deformation disturbs the pure shear stress condition all over the region between the notches. In this work, we used a configuration of the specimen and a supporting condition similar to the ASTM standard. To reduce the large deformation of the specimen, we should examine the testing condition in detail. If the catastrophic failure occurs between the notches without large deformation of the specimen, the shear strength can be obtained properly, and we can say that the Iosipescu shear test is the best method for determining the shear properties of wood.

Conclusions

We evaluated the method for measuring shear properties of wood by the Iosipescu shear test and obtained the following results.

1. The Iosipescu shear test effectively measures shear modulus and yield shear stress.
2. To measure the shear strength by the Iosipescu shear test properly, we should examine the configuration of the specimen and the supporting condition in more detail.

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