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Heng Xu · Chiaki Tanaka · Tetsuya Nakao
Masahiro Yoshinobu · Hiroyuki Katayama

Evaluation of rolling shear strength of plywood by flexural vibration method*

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Abstract The rolling shear strength of plywood was evaluated using a flexural vibration test. Test specimens were lauan and Douglas fir three-ply plywoods made from thick veneers. The dynamic shear and Young's moduli were determined using the flexural vibration method, which involved in-plane and out-of-plane flexural vibration. The rolling shear strength was determined using the static destructive method, which is dependent on the direction of the lathe check in the core veneer. Before and after accelerated aging treatments were conducted, there were relations between out-of-plane dynamic properties (out-of-plane shear and Young's moduli) and its rolling shear strength. It was concluded that the rolling shear strength is related not only to the shear property of the core but the flexural stiffness of two faces when the deformation of out-of-plane plywood was not restrained.

Key words Plywood · Rolling shear · Young's modulus · Shear modulus · Flexural vibration

Introduction

The dynamic elastic properties of materials provide useful information for evaluating their strength properties. In other words, the dynamic Young's modulus is correlated with static bending strength, although it is not the only factor affecting the strength.[1] The static characteristics of wood-based panels were evaluated using the in-plane and out-of plane flexural vibration technique from previous research.[2,3] The variations of the dynamic elastic moduli and the factors related to the strength properties were discussed for particleboard and medium-density fiberboard (MDF) during immersion treatments. There were relations between dynamic elastic properties and correlative strength properties that involve dynamic Young's moduli and the bending strength (MOR), internal bond (IB) strength, and so on.[3]

For structural plywood constructed with a thick core, the lower rolling shear strength of the core could have a negative influence on the structural strength of certain structural members made either entirely or partially from structural plywood (e.g., box or I-beams with plywood).[4] In this study the variations of dynamic elastic moduli and static rolling shear strengths during the aging using the immersion treatment and their relations were discussed.

Materials and methods

Materials

The experimental panels were three-ply hardwood and softwood plywoods. The veneers used were 3-mm thick lauan (*Shorea negrosensis Foxw.*) and Douglas fir (*Pseudotsuga menziesii Franco*). The qualities of the veneers are listed in Table 1. The quality of lathe checks – depth, frequency (density interval), and entering angle – was investigated by a "scale lape." Compared with the quality of lathe checks of lauan and Douglas fir veneers, it was found there were more lathe checks per unit length for the lauan veneer, but their depth was shallower than that in Douglas fir veneer. In addition, the entering angle and shape were different between them.

To reduce the effect of glue-line aging on mechanical properties during the immersion treatment, the phenol resorcinol formaldehyde resin (D-33; Oshika Resin, Tokyo, Japan) was applied to each glue line at a spread rate of 25 g/900 cm^2. The phenol resorcinol formaldehyde resin is an adhesive of high bonding strength and durability.

H. Xu · C. Tanaka (✉) · T. Nakao · M. Yoshinobu · H. Katayama
Interdisciplinary Faculty of Science and Engineering, Shimane University, Matsue 690-0823, Japan
Tel. +81-852-32-6562; Fax +81-852-32-6598
e-mail: chiaki@rikoshimane-u.ac.jp

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Table 1. Quantity of lauan and Douglas fir veneers

Type of veneer	Thickness (mm)	Lathe check		
		Depth (%)	Frequency	Angle (°)
Lauan	3.25	56	45.5	25–32
Douglas Fir	3.18	76	13.7	45–75

The depth is a ratio of the average lathe check depth and the veneer thickness. The frequency is number per 10-mm length. The angle is the enter angle of lathe checks.

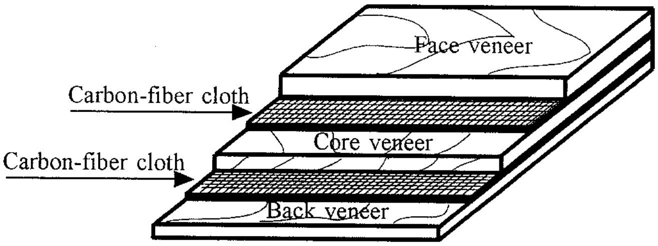


Fig. 1. Construction of fiber-reinforced plywood

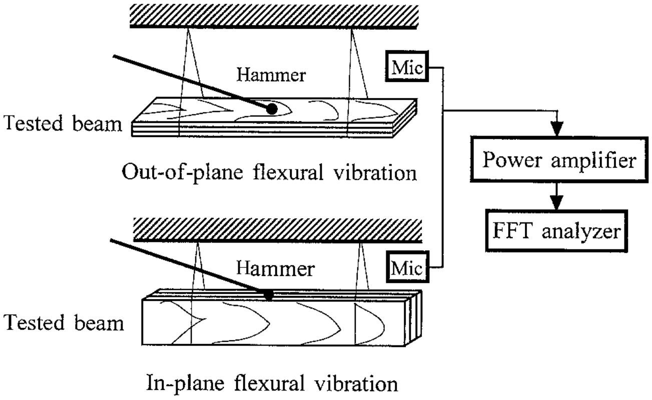


Fig. 2. Flexural vibration methods

The function of fiber reinforcement to rolling shear in plywood was also investigated. The fiber-reinforced plywood was constructed by placing two pieces of cross-woven graphite cloth (TR3110M; Mitsubishi Rayon, Tokyo, Japan) impregnated with phenol-formaldehyde resin (TD-62; Oshika Resin) between veneers. The construction is shown in Fig. 1. Other manufacturing conditions were the same as above.

All experimental panels (300 × 300 mm) were fabricated in the laboratory. Four panels were prepared for each of the plywoods. Panels were hot-pressed at 98 kPa and at 145°C for 6 and 9 min for the three-ply and fiber-reinforced plywoods, respectively.

Dynamic flexural vibration testing method

The Timoshenko-Goens-Hearmon (TGH) flexural vibration method was used to determine dynamic shear and Young's moduli of in-plane and out-of-plane plywood. With Timoshenko theory,[5] Young's modulus of a beam is decreased by the shear effect if the depth/span ratio is relatively large or if the beam is excited at high frequencies, which is explicitly described by Goens's formula.[6] Hearmon proposed a method for measuring Young's modulus (E) and shear modulus (G) with beams that are rather short and are influenced by the shear effect.[7] The test beam of plywood was supported by threads at two nodes and generated by hitting. An FFT analyzer was used to record vibration frequencies. Dynamic shear and Young's moduli were calculated at the same time using several resonance frequencies. The in-plane and out-of-plane shear and Young's moduli were obtained using in-plane and out-of-plane flexural vibration techniques. The testing methods are shown in Fig. 2. The length of a beam parallel to the face grain was 300 mm. The width and the depth of a beam were 50 mm and equaled the thickness of the plywoods, respectively. Four beams were taken and tested for each value.

Static rolling shear testing method

After the dynamic elastic properties were determined, the static rolling shear strength was measured with small samples (80 × 25 mm) cut from the above tested beams. The Okuma method was used, in which the size of specimens and the testing method were similar to those used for determining the glue-line shear strength of plywood.[8] The cutting notches were cut only to the middle of the core veneer. The distance between them was 20 mm. Depending on the shear force direction to the lathe checks in the core veneer, the specimens were classified as the open type (O type) or the closed type (C type). The specimens are shown in Fig. 3. During testing the deformation of out-of-plane plywood was not restrained when the core veneer was destroyed by rolling shear. The shear strengths were the average of eight specimens for at least each of two types.

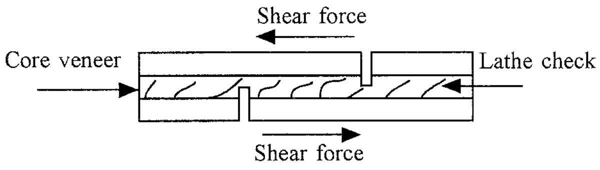
Accelerated aging treatments

Two types of accelerated aging treatment were applied. One consisted of 3-h immersion in water at 60°C and then 20-h drying at 60°C. The other contained 4-h boiling and 20-h drying at 60°C, with the steps repeated twice in the same cycle. After the accelerated aging, specimens were conditioned at 20°C and 50% relative humidity (RH) for 1 week to obtain a certain moisture content. The dynamic elastic properties and static rolling shear strength were determined before and after the two immersion treatments.

Results and discussion

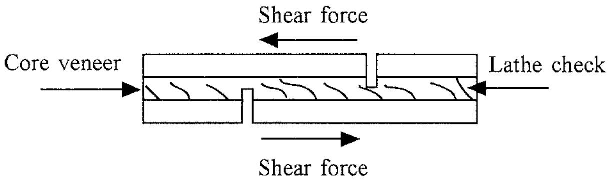
Relations between dynamic shear moduli and rolling shear strength

The dynamic shear moduli, that is, the in-plane shear modulus (G_i) and the out-of-plane shear modulus (G_o), reflects the average shear properties at all thicknesses and core layers, respectively, if the test material is not homogeneous in thickness.[3] In other words, the out-of-plane shear modulus could be used as a factor to evaluate the shear property of the core layer.



"O type" specimen

(Shear force is opposite to the direction of lathe check in the core)



"C type" specimen

(Shear force is at the direction of lathe check in the core)

Fig. 3. Specimens for the rolling shear strength test

Generally, it is believed that the rolling shear properties of plywood are mainly determined by the core veneer, the grain of which is perpendicular to the shear direction.[4] Also, there is a closer relation between the depth and frequency of the lathe check in core veneer and the rolling shear strength. The more lathe checks and the deeper they are, the lower is the strength of the rolling shear.[8]

From the dynamic shear moduli of lauan and Douglas fir plywoods listed in Table 2, it can be seen that the G_i and G_o of lauan plywood were much higher than those for Douglas fir plywood under normal condition. G_i was higher than G_o in the same condition for each kind of plywood. The reduction of G_o was marked with aging, and the residual G_o was only about 50% after the boiling treatment. Because the G_o reflects the core layer property, it may be stated that the shear modulus of core veneer was lower when the shear force was perpendicular, rather than parallel, to the grain. As the lathe checks in the core increased in number and became deeper during aging, the G_o decreased.

The rolling shear strengths (τ_r) of two types and their averages are listed in Table 3. The values for the C type were similar for the two kinds of plywood, but the values for the O type were higher for Douglas fir plywood than those for lauan plywood. After aging, the values for O type, C type, and their averages decreased owing to the change of lathe check in the core veneer.

Table 2. Dynamic Young's modulus and shear modulus before and after accelerated aging treatments

Types of plywood	Normal				Aging I				Aging II			
	G_i	G_o	E_i	E_o	G_i	G_o	E_i	E_o	G_i	G_o	E_i	E_o
Three-ply plywood												
Lauan	0.46	0.32	10.94	12.84	0.40	0.27	8.41	11.10	0.38	0.16	8.41	9.14
Douglas Fir	0.35	0.19	14.29	14.56	0.32	0.17	8.28	11.93	0.25	0.11	6.96	9.26
Fiber-reinforced plywood												
Lauan	0.74	0.38	11.20	15.00	0.68	0.35	11.05	14.55	0.58	0.28	10.25	13.75
Douglas Fir	0.65	0.22	12.51	15.65	0.53	0.19	13.20	15.25	0.45	0.18	10.55	13.33

Units are GPa: G_i, in-plane shear modules; G_o, out-of-plane shear modulus; E_i, in-plane Young's modulus; E_o, out-of-plane Young's modulus. Normal, before aging treatment; Aging I, 3-h immersion in water at 60° ± 3°C, then 20-h drying at 60° ± 3°C; Aging II, 4-h boiling, then 20-h drying at 60° ± 3°C, repeated twice in same cycle.

Table 3. Rolling shear strengths before and after various accelerated aging treatments

Types of plywood	Normal			Aging I			Aging II		
	C type	O type	Avg.	C type	O type	Avg.	C type	O type	Avg.
Three-ply plywood									
Lauan	2.19 (0.16)	1.37 (0.10)	1.77	1.56 (0.07)	1.09 (0.22)	1.32	1.10 (0.11)	0.81 (0.08)	0.95
Douglas Fir	2.09 (0.32)	1.80 (0.37)	1.94	1.64 (0.15)	1.48 (0.12)	1.56	1.05 (0.14)	0.97 (0.76)	1.00
Fiber-reinforced plywood									
Lauan	2.57 (0.13)	2.43 (0.18)	2.50	2.35 (0.18)	2.36 (0.15)	2.36	2.18 (0.22)	1.95 (0.30)	2.07
Douglas Fir	2.85 (0.21)	2.76 (0.25)	2.81	2.51 (0.15)	2.05 (0.23)	2.28	2.45 (0.17)	1.93 (0.12)	2.19

Units are MPa. Numbers in parentheses indicate standard deviation. Accelerated aging treatments are the same as in Table 2.

The relations between the dynamic shear moduli and the rolling shear strengths were explored. G_i did not show a close relation with τ_r, whereas G_o showed a linear correlation with τ_r (Fig. 4). It was proved that G_o and τ_r are mainly determined by the properties of the core layer and decrease together along with the change of the lathe check in the core veneer during aging. However, the correlative relations between G_o and τ_r were described using different regression equations based on the species (lauan or Douglas fir) and the type of specimen (O type and C type).

Relations between dynamic Young's moduli and rolling shear strength

The in-plane and out-of-plane Young's moduli were obtained in the same time as the in-plane and out-of-plane shear moduli, as shown in Table 3. When the out-of-plane (E_o) and in-plane (E_i) Young's moduli were compared, the difference between them was not as marked as it was between the dynamic shear moduli. They also decreased somewhat after aging. In general, it is believed that E_o reflects the flexural property of face layers, and E_i is the average flexural property of all thickness.[3] When E_o was compared with τ_r, it was found that there were correlative relations between them (Fig. 5). The higher the E_o, the higher was the τ_r, suggesting that the rolling shear failure in the core was restricted by two face layers when their deformation of out-of-plane flexure was in a free condition. In this case the face materials with high stiffness, which were bonded on two faces of the core, were helpful for increasing the rolling shear strength of the core when the shear force was intended to roll the wood fiber. It also explained why the results from Okuma method are lower than those from the ASTM method in which the out-of-plane flexure is restrained by two steel plates.[9]

Evaluation of rolling shear strength of fiber-reinforced plywood

That the strong graphite cloth as reinforcement was inserted between the veneers was advantageous for improving the elastic property and strength of plywood.[10] As a supplement to the above discussion, the dynamic elastic properties and static rolling shear strength of fiber-reinforced plywoods were evaluated during the same aging, The experimental results are listed in Tables 2 and 3.

Compared with control plywood, the G_o and E_o of a fiber-reinforced plywood were enhanced to different extents. During aging the descending rate of G_o and E_o became slower than that of the control. The rolling shear strength of the O type increased more markedly than did that of the C type owing to the fiber reinforcement. The descending rate of τ_r was as slow as that of G_o and E_o during the aging. It was proved that τ_r was correlative with G_o and E_o, as above. When cloth was inserted between veneers, the extension of lathe checks could be restricted during the aging process by a "cushioning effect."[11] Meanwhile, enhancement of τ_r was bound to follow reinforcement in E_o by

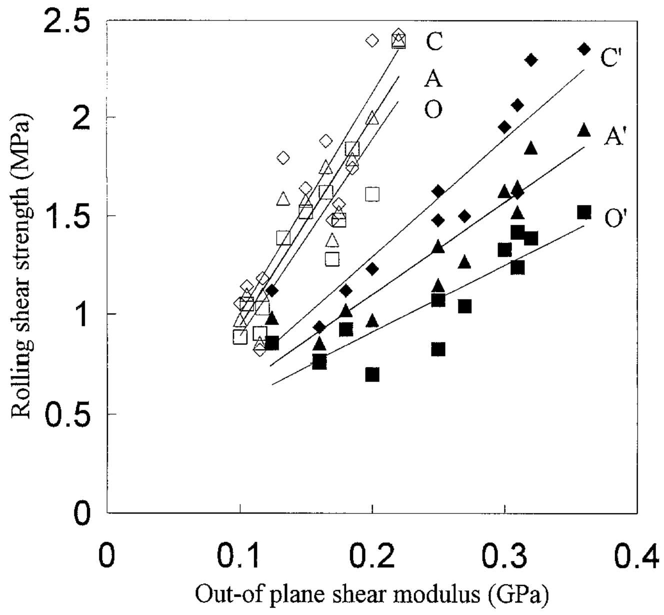


Fig. 4. Relation between the out-of-plane shear modulus and the rolling shear strength. *Open diamonds*, *C*, C type of Douglas fir plywood; *open squares*, *O*, O type of Douglas fir plywood; *open triangles*, *A*, average of C and O types of Douglas fir plywood; *filled triangles*, *C'*, C type of lauan plywood; *filled squares*, *O'*, O type of lauan plywood; *filled friangles*, *A'*, average of C and O types of lauan plywood. Rresults of linear regression between the out-of-plane shear modulus and the rolling shear strength are as follows. C: $Y = 11.22X - 0.122$ ($R = 0.876$); A: $Y = 10.58X - 0.116$ ($R = 0.915$); O: $Y = 10.01X - 0.115$ ($R = 0.903$); C', $Y = 5.978X + 0.096$ ($R = 0.92$); A': $Y = 4.698X + 0.160$ ($R = 0.932$); O', $Y = 3.417X + 0.224$ ($R = 0.877$)

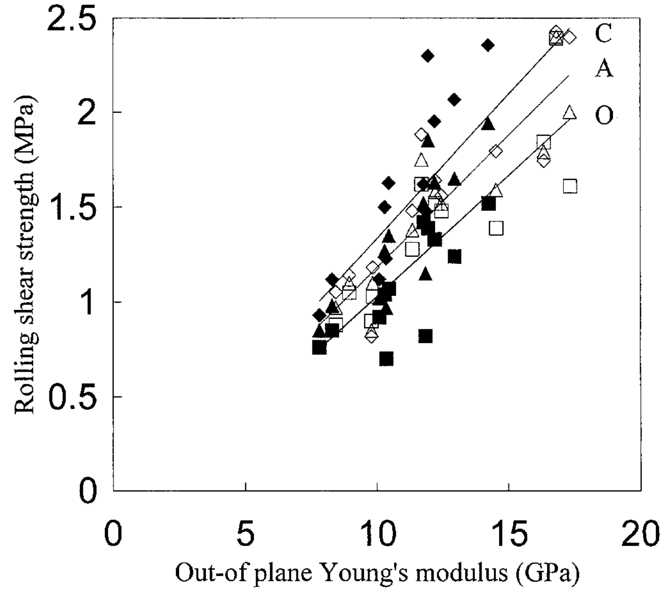


Fig. 5. Relation between the out-of-plane Young's modulus and the rolling shear strength. See Fig. 4 for explanation of symbols. Results of linear regression between the out-of-plane Young's modulus and the rolling shear strength are as follows. C: $Y = 0.127X - 0.241$ ($R = 0.837$); A (average): $Y = 0.139X - 0.206$ ($R = 0.881$); O: $Y = 0.127X - 0.180$ ($R = 0.828$)

a high-stiffness graphite cloth. That the graphite cloth is bonded on the faces of the core is advantageous for improving the rolling shear strength of the core and its durability.

Conclusions

The dynamic elastic properties, static rolling shear strength, and relation before and after the aging of plywood were discussed. The following conclusions have been drawn. For the three-ply plywood, the out-of-plane shear modulus and rolling shear strength mainly reflect the properties of the core veneer. Correlative relations between them existed. The values of the out-of-plane shear modulus and the rolling shear strength decreased together along with the change of the lathe check in the core veneer during aging. There were also correlative relations between the out-of-plane Young's modulus and the rolling shear strength when the faces were not restrained in out-of-plane flexure. In this case the rolling shear strength was related not only to the shear modulus of the core but also to the flexural stiffness of the face layer. The strong face layers were advantageous for restricting the rolling shear failure of the core in this case.

For fiber-reinforced plywood, in which fiber cloth was inserted between veneers, the dynamic elastic properties and the static rolling shear strength were enhanced. Inserting graphite fiber cloth between veneers is helpful for improving the rolling shear strength and durability of plywood.

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