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Fatigue of structural plywood under cyclic shear through thickness III: energy dissipation performance

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Abstract Wood and wood composites have viscoelasticity, and show a hysteresis loop in the stress–strain relationship during cyclic loading such that part of the mechanical work applied is dissipated in the materials. In this study, the energy dissipation performance of plywood specimens under cyclic shear through thickness was investigated. Fatigue testing was conducted under three loading conditions: a square waveform at a loading frequency of 0.5 Hz, a triangular waveform at 0.5 Hz, and a triangular waveform at 5.0 Hz. The stress level was determined to be 0.5, 0.7, and 0.9 of the static strength in shear through thickness. The energy dissipation ratio was defined as the ratio of energy loss per cycle to the strain energy per cycle, and was evaluated throughout the fatigue test. It was found that the energy dissipation ratio of a plywood specimen was kept constant during most of the fatigue process for a given stress level and loading condition. The energy dissipation performance was significantly dependent on stress level and loading condition, and became higher according to the damage intensity of cyclic load even if the same strain energy was applied.

Key words Energy dissipation performance · Loading waveform · Loading frequency · Shear through thickness · Plywood

Introduction

The fatigue of wood and wood composites has already been reported in past studies in regard to several influencing factors such as environmental and loading conditions. The single effect of loading waveform or loading frequency on the fatigue of wood and wood composites has been examined, and revealed that loading waveform and loading frequency affect the fatigue life of wood and wood composites, respectively.[1–7] We conducted fatigue testing of plywood specimens under shear through thickness considering not only the single effect but also the interaction of loading waveform and loading frequency.[8,9]

Wood and wood composites are well known to be viscoelastic materials, and show a hysteresis loop in the stress–strain relationship under cyclic loading. The area enclosed by a hysteresis loop, that is the energy dissipation, is considered to be one of the dynamic material properties. Essentially, it shows how much energy is dissipated due to the mechanical work applied to a material. The energy dissipation of wood and wood composites has not attracted much attention, whereas the energy dissipation of timber structures is generally considered as a structural performance with equivalent viscous damping. When the energy dissipation performance of wood and wood composites is clarified in addition to their strength and stiffness, it will contribute to deeper understanding of the performance of timber structures and new applications of wood and wood composites. Wood-based panels are frequently subjected to shear load through the thickness in the case of sheathing for bearing walls of residential houses and the web of I-joists.

The purpose of this study was to gain an understanding of the energy dissipation performance of plywood under cyclic shear through thickness.

Materials and methods

The commercial product classified as Japanese Agricultural Standard (JAS)[10] structural plywood, type special, class 2 was used for the experiments. The plywood panel consisted of three-ply veneers made of Russian larch (*Larix sibirica* Ledebour), and had a nominal thickness of 9 mm. The panel was stored in a testing room at a room temperature of 24°C and a relative humidity of 55% prior to testing.

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The procedures of specimen preparation and testing were essentially according to ASTM D 2719, *Method C; Two Rail Shear Test.*[11] Sixty specimens with a length of 350 mm and width of 240 mm were prepared from five panels. Twenty-seven specimens were actually used in the fatigue test in this study. The mean density and moisture content of the specimens were 0.55 ± 0.03 g/cm^3 and 8.8% ± 0.2%, respectively. Schematic illustration of the fatigue test of a plywood specimen under cyclic shear through thickness is shown in Fig. 1. To hold the specimen for the mechanical test, the lumber splints were bonded on its longitudinal edges with resorcinol resin glue. Then 14 bolt holes were drilled to fix two pairs of steel rails. A pair of steel rails were attached to the actuator of an electrohydraulic servo fatigue testing machine (EHF-UB5-10L, Shimadzu, Kyoto, Japan), and the other pair were anchored to the base table. A biaxial strain gauge (KFG-5-120-D16, Kyowa, Tokyo, Japan, 5 mm gauge length and 120 Ω resistance) was bonded at the center of the specimen surface with cyanoacrylate-based adhesive. Shear strain, load, and the displacement of the actuator were recorded simultaneously with a dynamic data logger (PCD-1000, Kyowa).

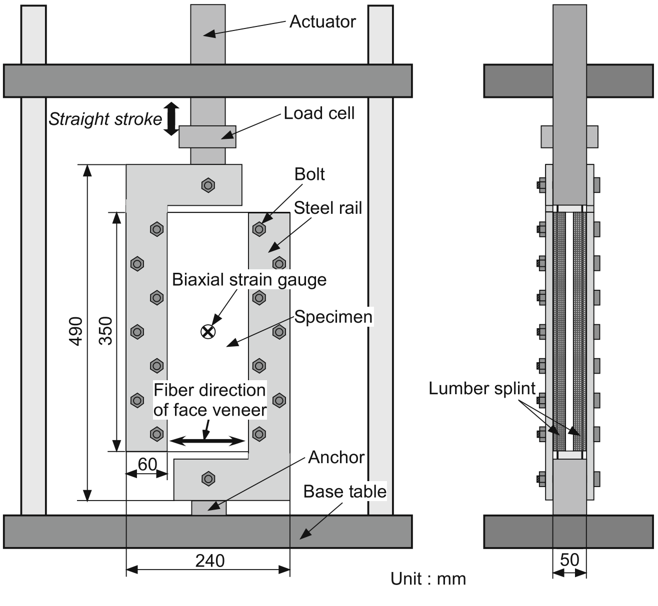

Fig. 1. Schematic illustration of the experimental setup

A nonreversed load was repeatedly applied to the specimens at stress levels (*SL*s) of 0.5, 0.7, and 0.9 in each of three loading conditions: a square waveform at a loading frequency of 0.5 Hz (Sq, 0.5 Hz), a triangular waveform at 0.5 Hz (Tr, 0.5 Hz), and a triangular waveform at 5.0 Hz (Tr, 5.0 Hz). Stress level (*SL*) was the ratio of the preset peak stress applied in the fatigue test to the mean static strength in shear through thickness. The mean static strength of plywood specimens was found to be 5.16 ± 0.35 MPa prior to the fatigue test. Three specimens were used at each stress level under a given loading condition. Further detailed description of the specimen preparation and testing methods is given in Part 1[8] of this study.

From the stress–strain hysteresis loop measured at each loading cycle, the energy loss per cycle (U_c), the strain energy per cycle (V_c), and the energy dissipation ratio (H_c) were evaluated. The energy loss per cycle (U_c) was the area enclosed by a hysteresis loop, and the strain energy per cycle (V_c) was the area surrounded by the loading curve of a hysteresis loop, the horizontal axis, and the vertical line passing the maximum point of applied stress. Details of the results on the strain energy per cycle of plywood specimens are reported in Part 1.[8] The energy dissipation ratio (H_c) was defined as the ratio of the energy loss per cycle to the strain energy per cycle (V_c) for each loading cycle. The average values of the strain energy per cycle and energy dissipation ratio of a specimen under fatigue loading were defined as mean strain energy per cycle (V_m) and mean energy dissipation ratio (H_m), respectively.

Results and discussion

Hysteresis loop area and energy dissipation performance in fatigue process

Figure 2 shows the hysteresis loops of plywood specimens measured at the first loading cycle. A typical loop is shown for each stress level and loading condition. The shapes of hysteresis loops were different according to the loading condition at each stress level. For the square waveform at 0.5 Hz, the shear stress instantly reached and maintained a peak value during the loading phase of one cycle. The viscoelastic creep developed while the peak stress was kept constant, and consequently the hysteresis loop became

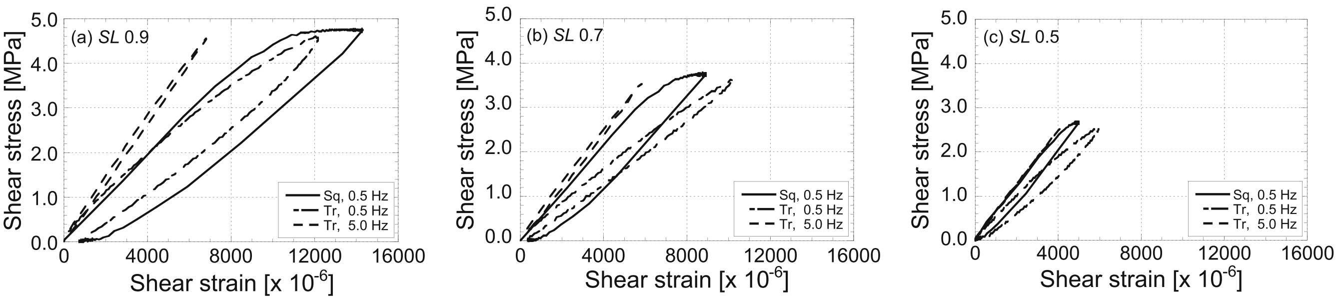

Fig. 2a–c. Typical hysteresis loops for the first loading cycle in three loading conditions for **a** stress level (*SL*) = 0.9, **b** *SL* = 0.7, and **c** *SL* = 0.5. *Sq*, square waveform; *Tr*, triangular waveform

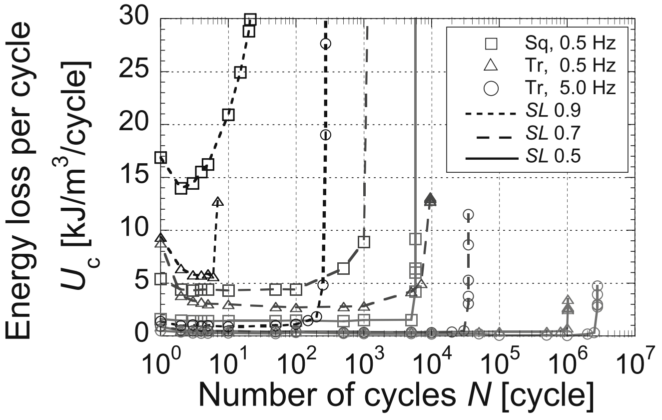

Fig. 3. Typical changes in energy loss per cycle during fatigue

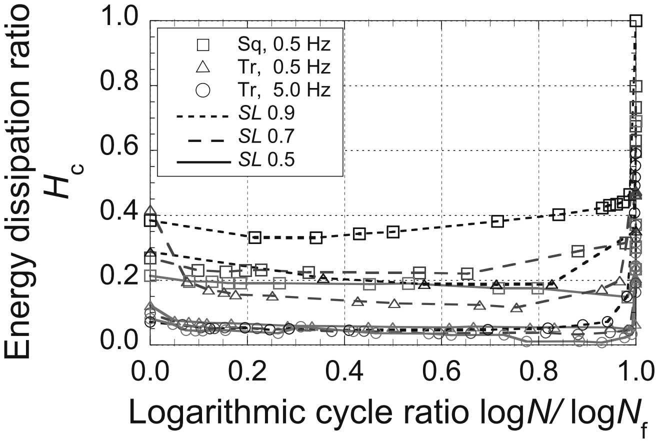

Fig. 4. Typical energy dissipation ratio during normalized fatigue process

large. For the triangular waveform, the hysteresis loop was larger at 0.5 Hz than at 5.0 Hz. This is because the loading duration per cycle was about ten times longer at 0.5 Hz than that at 5.0 Hz, and the plywood specimen showed time-dependent deformation such as anelastic strain at 0.5 Hz more remarkably than at 5.0 Hz. These results demonstrate that the hysteresis loop of a plywood specimen is sensitive to the stress level, loading waveform, and frequency, and a plywood specimen probably has strong viscoelasticity under cyclic shear through thickness.

The typical changes in energy loss per cycle (U_c) with increasing number of loading cycles (N) are shown in Fig. 3. It was found that the energy loss per cycle of a plywood specimen decreased from the first loading cycle to the second cycle, especially at high stress levels. Wood and wood composite are generally heterogeneous. For a plywood specimen, delaminated areas between veneer sheets and micro cracks in veneer sheets can be relatively weak under load. We consider that these inherent weak parts have less strength than other parts in a plywood specimen and incur damage due to external load below static strength. Under cyclic loading, these originally weak parts are probably damaged in the first loading cycle and do not remain for the second loading cycle. As a consequence, the energy loss in the first cycle was larger than that in the following cycles. Then energy loss per cycle showed a certain value with the cumulative loading cycle, and increased sharply up to fatigue failure. These changes in energy loss per cycle were common phenomena in all specimens irrespective of stress level and loading condition. Strain energy per cycle was also approximately constant from the first cycle to immediately before fatigue failure in each stress level and loading condition, as reported in Part 1.[8]

On the basis of the above results for energy loss per cycle and strain energy per cycle, the energy dissipation ratio of a plywood specimen was investigated on the fatigue development. Figure 4 shows the typical changes in energy dissipation ratio (H_c) with the logarithmic cycle ratio ($\log N/\log N_f$). The fatigue development of every specimen was normalized with the logarithmic cycle ratio ($\log N/\log N_f$) defined as the ratio of the logarithm of the number of loading cycles ($\log N$) to the logarithm of the fatigue life of a specimen ($\log N_f$), but not a cycle ratio (N/N_f). In Part 1[8] of this study, the strain energy analysis revealed that the fatigue process and failure criterion of a plywood specimen could be expressed with the accumulation of strain energy, and the accumulation of strain energy was linearly related to the number of loading cycles on a logarithmic scale. Then we considered that the fatigue damage accumulated with the logarithmic number of loading cycles in a plywood specimen. This idea is also supported by the results demonstrated in other reports that the mechanical properties of wood and wood composites change with the logarithmic number of loading cycles under cyclic loading.[4,7,12–15] Furthermore, we recently proposed the cumulative fatigue damage theory based on the logarithmic number of loading cycles.[16]

As shown in Fig. 4, the energy dissipation ratio of a plywood specimen was kept at a constant value during the logarithmic cycle ratio from 0.1 through 0.9, whereas it varied according to the stress level and loading condition. Therefore, the energy dissipation performance of a plywood specimen is maintained throughout most of the fatigue development in each stress level and loading condition under cyclic shear through thickness. This phenomenon can be explained as follows. In the past studies on the tensile fatigue of solid wood,[2,3] energy loss consists of the loss related to viscoelasticity and the loss generated by fatigue damage. The loss related to viscoelasticity is dependent on the loading waveform, whereas it is independent of the number of loading cycles.[2] Then the viscoelastic loss per cycle of a plywood specimen is roughly assumed to be constant during cyclic loading in each stress level and loading condition. The loss per cycle by fatigue damage seems to be also constant during most of the fatigue life in each stress level and loading condition, because the residual strain of a plywood specimen monotonically increases immediately before fatigue failure under cyclic shear through thickness.[7] Additionally, the strain energy per cycle of a plywood specimen shows a constant value under fatigue loading.[8] These are the reasons why the energy dissipation performance of a plywood specimen is maintained throughout most of the

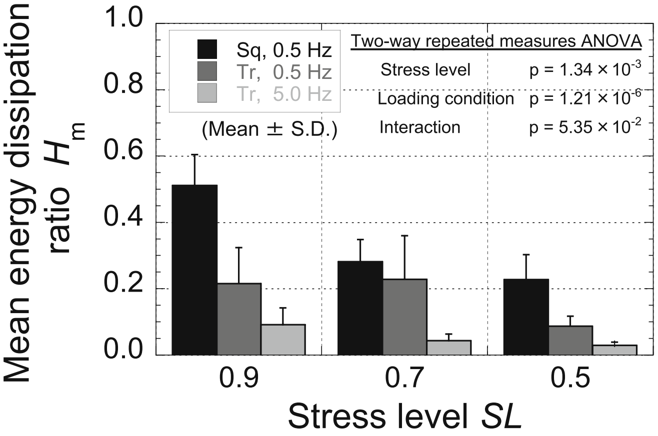

Fig. 5. Mean energy dissipation ratio in each stress level and loading condition. Each column shows mean ± standard deviation for $n = 3$

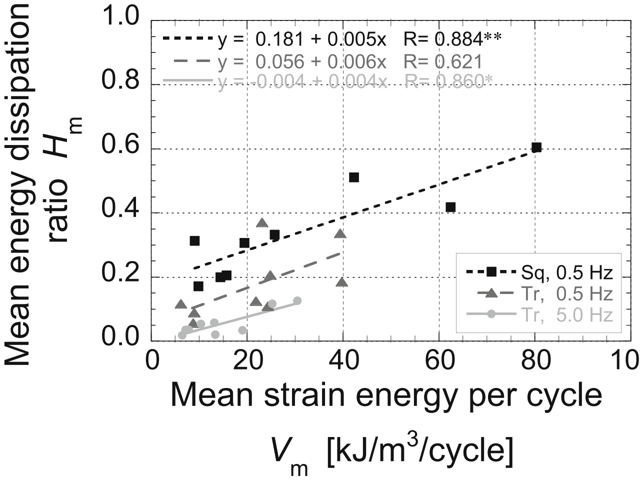

Fig. 6. Relationship between mean energy dissipation ratio and mean strain energy per cycle in each loading condition. *Asterisk*, significant at 5% significance level; *double asterisk*, significant at 1% significance level

fatigue process in a given stress level and loading condition under cyclic shear through thickness. Stress level and loading condition often vary in actual loading situations. Further investigation should be conducted on the energy dissipation performance of plywood specimens under variable shear load through thickness.

Effects of stress level and loading condition on energy dissipation performance

Figure 5 shows the mean energy dissipation ratio (H_m) for each stress level and loading condition. The mean energy dissipation ratio of a plywood specimen was found to be larger at higher stress levels for each loading condition. Among the three loading conditions, cyclic load in a square waveform at a loading frequency of 0.5 Hz induced the largest mean energy dissipation ratio, and the load in a triangular waveform at 5.0 Hz gave the smallest mean energy dissipation ratio at each stress level. Two-way repeated measures of analysis of variance (ANOVA) clarified that the main effects of stress level and loading condition were statistically significant at the significance level of 1%, whereas the interaction between stress level and loading condition was not significant at the 5% significance level. These results demonstrate that the energy dissipation performance of a plywood specimen is significantly dependent on stress level and loading condition.

The relationship between the mean energy dissipation ratio (H_m) and the mean strain energy per cycle (V_m) is shown in Fig. 6. The relationship was found to be linear in each loading condition. The regression lines were statistically significant for the square waveform at 0.5 Hz and the triangular waveform at 5.0 Hz, but not for the triangular waveform at 0.5 Hz. The slope of the relationship was almost the same among the three loading conditions. On the other hand, the intercept of the relationship was larger in the order of triangular waveform at 5.0 Hz < triangular waveform at 0.5 Hz < square waveform at 0.5 Hz. These results demonstrate that the energy dissipation performance of a plywood specimen is higher in the same order even if the same strain energy is applied to the specimen. These results are probably attributable to the remarkable viscoelasticity of plywood specimens. Between the two loading frequencies of 0.5 and 5.0 Hz, the loading duration at 0.5 Hz was probably sufficient so that the viscoelastic behavior of plywood specimens appeared significantly. Plywood specimen showed higher hysteresis loss for the triangular waveform at 0.5 Hz than the triangular waveform at 5.0 Hz, as shown in Fig. 2. In addition, for the square waveform at 0.5 Hz, constant peak stress induced viscoelastic creep during the loading phase. The square waveform resulted in the largest energy dissipation among the three loading conditions. Based on these loading characteristics, the square waveform at 0.5 Hz had the most damaging intensity of cyclic load among the three loading conditions. As reported in Part 1,[8] the fatigue life of a plywood specimen depends on the loading condition, and it is shorter in the order of triangular waveform at 5.0 Hz > triangular waveform at 0.5 Hz > square waveform at 0.5 Hz. The plywood specimen is consequently damaged to a larger extent in the order of triangular waveform at 5.0 Hz < triangular waveform at 0.5 Hz < square waveform at 0.5 Hz under cyclic loading. That is to say, the damage intensity of cyclic load is higher in the same order as the mean energy dissipation ratio. These results suggest that a plywood specimen shows higher energy dissipation performance according to the higher damage intensity of cyclic load under shear through thickness. This is considered to be a characteristic material property of plywood that was previously unknown. The energy dissipation performances of wood and wood composites are not always the same because there are various kinds of wood and wood composites. It anticipated that wide-ranging studies will further investigate the energy dissipation performance of wood and wood composites in addition to strength and stiffness.

Conclusions

Hysteresis in the stress–strain relationship under cyclic loading was evaluated as energy dissipation performance in this study. The energy dissipation performance of a plywood specimen under cyclic shear through thickness was kept constant during most of the fatigue process for a given stress level and loading condition. Stress level and loading condition significantly affected the energy dissipation performance of plywood specimens, and the performance became higher according to the damage intensity of the cyclic load even if the same strain energy was applied to the specimen.

References

1. Marsoem SN, Bordonné PA, Okuyama T (1987) Mechanical responses of wood to repeated loading II. Effect of wave form on tensile fatigue. Mokuzai Gakkaishi 33:354–360
2. Kohara M, Okuyama T (1993) Mechanical responses of wood to repeated loading VI. Energy-loss partitioning scheme to predict tensile fatigue lifetime. Mokuzai Gakkaishi 39:1226–1230
3. Kohara M, Okuyama T (1994) Mechanical responses of wood to repeated loading VII. Dependence of energy loss on stress amplitude and effect of wave forms on fatigue lifetime. Mokuzai Gakkaishi 40:491–496
4. Thompson RJH, Bonfield PW, Dinwoodie JM, Ansell MP (1996) Fatigue and creep in chipboard. Part 3. The effect of frequency. Wood Sci Technol 30:293–305
5. Clorius CO, Pederson MU, Hoffmeyer P, Damkilde L (2000) Compressive fatigue in wood. Wood Sci Technol 34:21–37
6. Gong M, Smith I (2003) Effect of waveform and loading sequence on low-cycle compressive fatigue life of spruce. J Mater Civil Eng 15:93–99
7. Sugimoto T, Sasaki Y (2006) Effect of loading frequency on fatigue life and dissipated energy of structural plywood under panel shear load. Wood Sci Technol 40:501–515
8. Sugimoto T, Sasaki Y, Yamasaki M (2007) Fatigue of structural plywood under cyclic shear through thickness I: fatigue process and failure criterion based on strain energy. J Wood Sci 53: 296–302
9. Sugimoto T, Sasaki Y, Yamasaki M (2007) Fatigue of structural plywood under cyclic shear through thickness II: a new method for fatigue life prediction. J Wood Sci 53:303–308
10. Japanese Agricultural Standards (2003) JAS for plywood. Japan Plywood Inspection Corporation, JPIC-EW.SE03-01, pp 1–98
11. American Society for Testing and Materials (2005) ASTM D2719. Standard test method for structural panels in shear through-the-thickness. American Society for Testing and Materials, West Conshohocken, PA., Vol. 04.10. Wood. Section-7, pp 395–403
12. Hacker CL, Ansell MP (2001) Fatigue damage and hysteresis in wood-epoxy laminates. J Mater Sci 36:609–621
13. Sasaki Y, Yamasaki M (2004) Effect of pulsating tension-torsion combined loading on fatigue behavior in wood. Holzforschung 58:666–672
14. Sasaki Y, Yamasaki M, Sugimoto T (2005) Fatigue damage in wood under pulsating multiaxial-combined loading. Wood Fiber Sci 37:232–241
15. Sugimoto T, Yamasaki M, Sasaki Y (2006) Fatigue and hysteresis effects in wood-based panels under cyclic shear load through thickness. Wood Fiber Sci 38:215–228
16. Sugimoto T, Sasaki Y (2007) Fatigue life of structural plywood under two-stage panel shear load: a new cumulative fatigue damage theory. J Wood Sci 53:211–217