J Wood Sci (2007) 53:296–302
DOI 10.1007/s10086-006-0864-6

ORIGINAL ARTICLE

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Fatigue of structural plywood under cyclic shear through thickness I: fatigue process and failure criterion based on strain energy

Received: April 19, 2006 / Accepted: October 25, 2006 / Published online: March 31, 2007

Abstract The fatigue behavior of plywood specimens under shear through thickness was examined on the basis of strain energy to obtain common empirical equations for the fatigue process and failure criterion under various loading conditions. Specimens were cut from commercial plywood panels of 9-mm thickness. Loading conditions were set as follows: 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. Peak stress applied was determined to be 0.5, 0.7, and 0.9 of static strength, that is, stress levels of 0.5, 0.7, and 0.9. The stress–strain relationships were measured throughout the fatigue test, and the strain energy was obtained at each loading cycle. Loading conditions apparently affected the relationship between stress level and fatigue life. On the other hand, the relationship between mean strain energy per cycle and fatigue life was found to be independent of loading conditions. Mean strain energy per cycle obtained as the fatigue limit was 5.85 kJ/m^3 per cycle. Assuming that the accumulation of strain energy is a fatigue indicator, the fatigue process and failure criterion for the plywood specimens under the three loading conditions were commonly expressed by the relationship between cumulative strain energy and loading cycles.

Key words Loading waveform · Loading frequency · Strain energy · Shear through thickness · Plywood

Introduction

Fatigue occurs when a material is subject to cyclic stresses over a long time. Structural materials in constructions such as bridges, buildings, and houses are exposed to cyclic load during service. Wood and wood composites are major construction materials, and, therefore, fatigue in wood and wood composites should be fully elucidated to design timber structures more efficiently and with improved safety.

The fatigue of wood and wood composites has already been investigated considering environmental and loading conditions because these conditions change in actual construction situations. The effects of loading conditions, such as loading waveform and loading frequency, on the fatigue behavior of these materials have been reported in several studies. Marsoem et al.[1] examined the tensile fatigue of solid wood in triangular, sinusoidal, and square waveforms and revealed that the square waveform was the most damaging. A similar result was obtained for the compressive fatigue of solid wood.[2] Kohara and Okuyama[3–5] proposed the criterion of fatigue life independent of loading waveform in the tensile fatigue life of solid wood based on its strain energy loss behavior. Loading frequency also affects the fatigue life of wood and wood composites.[6–10] The number of loading cycles to failure at a certain stress level was found to be longer with a higher loading frequency in all of these studies, although the frequency dependence of fatigue life was affected by stress level differently among these studies.

The single effect of loading waveform or loading frequency on the fatigue of wood and wood composite has been discussed in many studies, as described above. However, loading waveform and loading frequency are likely to affect fatigue behavior in a complicated manner because they change simultaneously in actual situations. It is, therefore, necessary to examine fatigue behavior in consideration of various loading conditions to elucidate the fatigue development and failure mechanism of wood and wood composites. On the assumption that wood-based panels used as the sheathing of bearing walls of residential houses and the web of I-joists are frequently subjected to shear load through the thickness, cyclic shear load through the thickness under three loading conditions was applied to plywood specimens in this study. The main objective of this study was to systematically reveal the fatigue behavior

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of wood and wood composites under various loading conditions.

Materials and methods

Details of the preparation of the test specimens and the test method for the fatigue of structural plywood under shear load through the thickness were described in our recent report.[10] Here, specimen preparations and experimental methods are briefly described.

Specimen preparations

The plywood panel used in this study was classified as Japanese Agricultural Standard (JAS)[11] structural plywood, type special, class 2. The veneer was made of Russian larch (*Larix sibirica* Ledebour). The plywood panel had a nominal thickness of 9 mm, and consisted of three-ply veneers. The density of the plywood was 0.55 ± 0.03 g/cm^3 (mean ± standard deviation) and the moisture content was 8.8% ± 0.2% under the testing conditions of 24°C room temperature and relative humidity of 55%.

The test specimens were prepared according to ASTM D 2719 *Method C: Two Rail Shear Test*.[12] Sixty specimens of 350 (length) × 240 mm (width) were obtained from five panels so that the shorter side of the specimen was parallel to the fiber direction of the face veneer, as shown in Fig. 1. Ten specimens were assigned to the static test to determine the static strength under shear through the thickness, and the others were randomly assigned to the fatigue tests in a series of studies conducted in our laboratory. Twenty-seven specimens were actually used in the fatigue test in this study.

Lumber splints were bonded to the longer sides on the surface of each specimen, using resorcinol resin glue, to reinforce and hold the specimen in both the static and fatigue tests. Seven bolt holes were made to fasten the splints to a pair of steel rails.

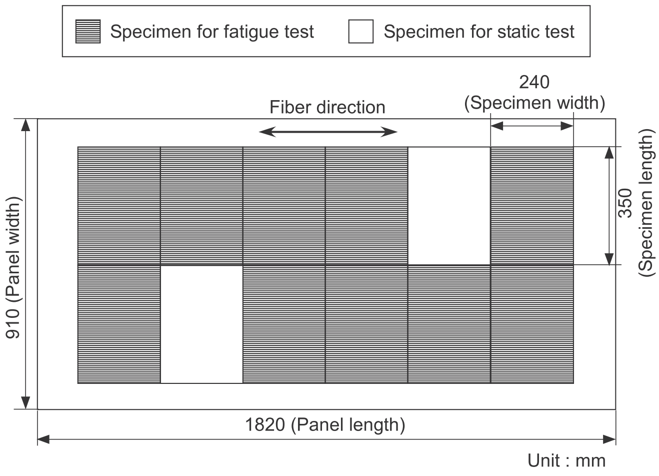

Fig. 1. Cutting pattern for removal of specimens from plywood panel

Fatigue test

The fatigue test under shear load through the thickness was conducted according to ASTM D2719 Method C by an electrohydraulic servo fatigue testing machine (EHF-UB5-10L, Shimadzu, Kyoto, Japan). The experimental conditions are listed in Table 1. A cyclic nonreversible load was applied longitudinally to the test specimen under three loading conditions: a square waveform (Sq) at a loading frequency of 0.5 Hz, a triangular waveform (Tr) at 0.5 Hz, and a triangular waveform at 5.0 Hz. To determine the single effect of loading waveform, the results under the first two loading conditions were compared. The results for the two loading conditions with Tr were compared to determine the single effect of loading frequency. The combined effects of loading waveform and loading frequency were examined by comparison of the results for Sq at 0.5 Hz and those for Tr at 5.0 Hz. Three stages equivalent to stress levels (*SL*s) of 0.5, 0.7, and 0.9 were determined according to the ratio of the preset peak stress (τ_{peak}) to the mean static strength in shear through thickness (τ_{static}). The mean static strength in shear through the thickness was found to be 5.16 MPa prior to the fatigue test. Three specimens were used at each stress level under respective loading conditions.

At the center of the specimen surface, shear strain was measured with a biaxial strain gauge (KFG-5-120-D16, Kyowa, Tokyo, Japan; 5 mm gauge length, 120 Ω resistance). The gauge was bonded to the specimen by cyanoacrylate-based adhesive. Shear strain, load, and the displacement of the actuator were recorded simultaneously with a dynamic data logger (PCD-1000, Kyowa). The data sampling frequencies were 100 Hz at a loading frequency of 0.5 Hz and 200 Hz at a loading frequency of 5.0 Hz. All the tests were carried out at a room temperature of 24°C and a relative humidity of 55%.

From these measurements, the hysteresis loop of the shear stress–strain relationship was obtained for each loading cycle. As shown in Fig. 2, the area surrounded by the loading curve of the hysteresis loop and the horizontal axis was the strain energy per cycle (V_c), which was calculated by numerical integration at each loading cycle. Strain energy per cycle was summed from the first cycle to the N^{th} loading cycle as cumulative strain energy at the N^{th} loading cycle (V_{ac}). Of note, the sum of strain energy from the first cycle to the number of cycles to failure (fatigue life, N_f) was

Table 1. Experimental conditions in fatigue test

Loading condition		Stress level (*SL*)	Number of test specimens
Waveform	Frequency (Hz)		
Square (Sq)	0.5	0.9	3
	0.5	0.7	3
	0.5	0.5	3
Triangular (Tr)	0.5	0.9	3
	0.5	0.7	3
	0.5	0.5	3
Triangular (Tr)	5.0	0.9	3
	5.0	0.7	3
	5.0	0.5	3

defined as the cumulative strain energy at failure (V_{acf}). Mean strain energy per cycle (V_m) was calculated by dividing the cumulative strain energy at failure (V_{acf}) by fatigue life (N_f).

Results and discussion

Relationships between stress level and number of cycles to failure (*S–N* relationships)

Figure 3 shows the *S–N* relationships for all specimens in the fatigue test. The vertical axis shows the stress level (*SL*), and the horizontal axis shows the number of cycles to failure, which is the fatigue life (N_f), on a logarithmic scale. The linear-logarithmic relationship between stress level and fatigue life was found to be negative for each loading condition. All regression lines were statistically significant at the 1% significance level. The fatigue life of the plywood specimen was highly dependent on loading conditions; it became longer in the order: square waveform at 0.5 Hz, triangular waveform at 0.5 Hz, and triangular waveform at 5.0 Hz. The effects of loading conditions on *S–N* relationships were statistically examined by analysis of covariance (ANCOVA) with checking of the assumption of parallelism.[13] The test for checking the assumption of parallelism indicated that the null hypothesis was not rejected at the 5% significance level (Table 2). Then ANCOVA showed that the adjusted means of three regression lines were significantly different at the 1% significance level (Table 2). Therefore, loading conditions affect the *S–N* relationships of plywood specimen under cyclic shear through the thickness.

Stress–strain relationships

The hysteresis loop of the shear stress–strain relationship was obtained during each loading cycle in the fatigue test. A hysteresis loop during a loading cycle consisted of the loading curve and the unloading curve. Figure 4 shows the loading curves of the hysteresis loops measured at the first loading cycle. A typical example is shown at each stress level under respective loading conditions. The shape of the loading curve in the square waveform at the loading frequency of 0.5 Hz was found to be characteristic among these three conditions, because peak stress was applied during most of the loading phase in one cycle. For the triangular waveform, the slope of the curve was steeper at 5.0 Hz than at 0.5 Hz owing to the higher loading rate. These results indicate that the deformation behavior of the plywood specimen depends on the loading conditions under cyclic shear through the thickness, even though the same value of stress was applied to the specimen. This is considered to be the reason the fatigue life of the plywood specimen is highly dependent on the loading conditions. Therefore, not only

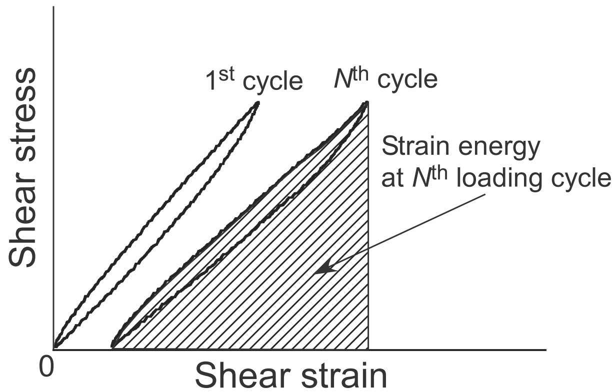

Fig. 2. Representation of strain energy per cycle

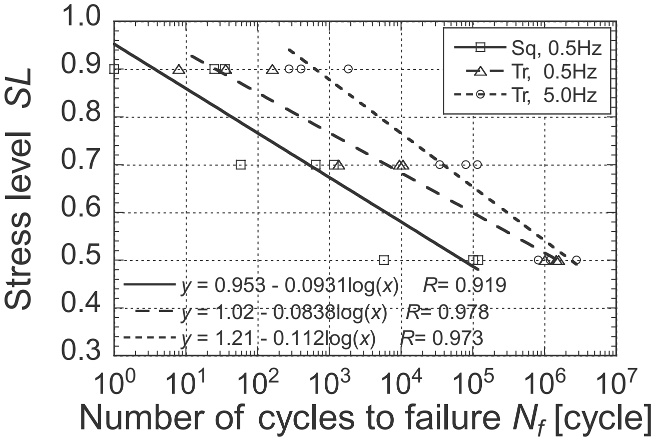

Fig. 3. Relationship between stress level (*SL*) and number of loading cycles to failure (N_f) for all specimens in fatigue test. *Sq*, square waveform; *Tr*, triangular waveform

Table 2. Analysis of covariance for relationships between stress level and number of cycles to failure under three loading conditions

Source	DF	Sum of squares	Mean square	*F*	Probability > *F*
Assumption of constant slope					
Regression	2	0.009	0.005	1.639	0.218
Error	21	0.060	0.003		
Corrected total	23	0.070	0.003		
Equality of adjusted means					
Adjusted mean	2	0.114	0.057	18.960	<0.001**
Adjusted error	23	0.070	0.003		
Adjusted total	25	0.184	0.007		

DF, degrees of freedom
** Significant at 1% level

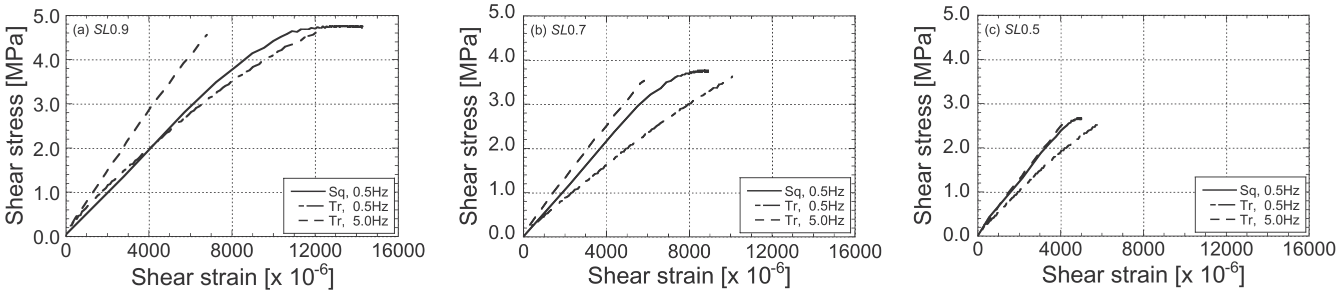

Fig. 4a–c. Typical loading curve of hysteresis loop measured at first loading cycle in fatigue test for **a** $SL = 0.9$, **b** $SL = 0.7$, **c** $SL = 0.5$

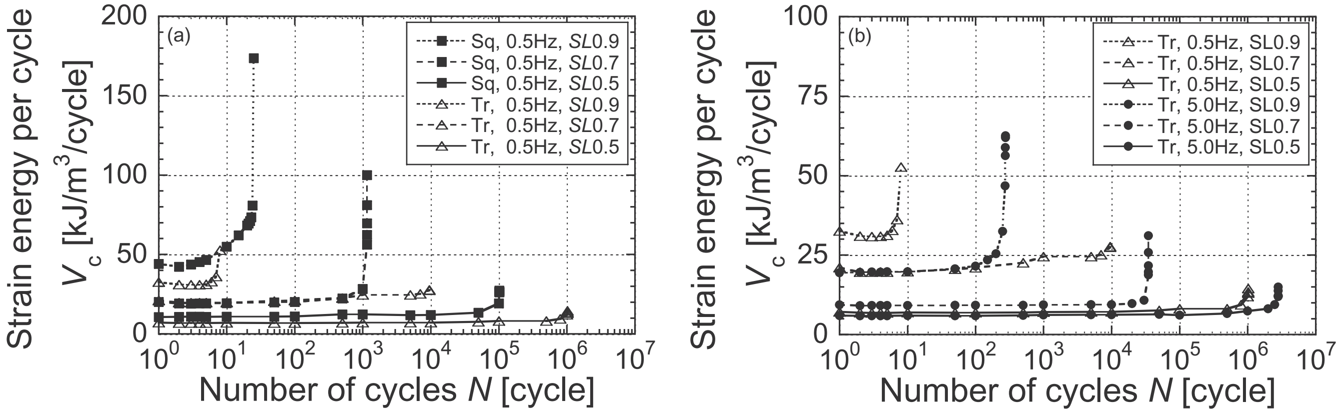

Fig. 5a, b. Typical fatigue-related change in strain energy per cycle (V_c). **a** Square waveform at loading frequency of 0.5 Hz and triangular waveform at the same frequency, and **b** triangular waveform at 0.5 Hz and 5 Hz

the stress level but also the strain should be taken into consideration to elucidate the fatigue behavior of plywood specimens under various loading conditions. We speculate that an appropriate parameter is the mechanical work done in a unit volume of a specimen per cycle, that is, the strain energy per cycle as given in Fig. 2. Strain energy per cycle reflects the deformation behavior of a plywood specimen during loading from zero to the peak value.

Strain energy per cycle during fatigue

The change in strain energy per cycle (V_c) with increasing number of loading cycles (N) is shown in Fig. 5. Figure 5a shows the results for the square and triangular waveforms at the loading frequency of 0.5 Hz, and Fig. 5b shows the results for the triangular waveform at 0.5 Hz and 5.0 Hz. A typical example is shown at each stress level under respective loading conditions. Strain energy per cycle showed a certain value throughout most of the fatigue life, and abruptly increased immediately before fatigue failure. Therefore, it is considered that a strain energy per cycle with approximately same value was applied to the plywood specimen from the first cycle to immediately before fatigue failure. The strain energy per cycle under each loading condition was larger at higher stress levels. Regarding the effect of loading waveform (Fig. 5a), strain energy per cycle for the square waveform tended to be larger than for the triangular waveform at each stress level. Figure 5b shows that a lower loading frequency induces a larger strain energy per cycle at each stress level. As the combination of these respective effects of loading waveform and loading frequency, strain energy per cycle for the square waveform at 0.5 Hz was larger than for the triangular waveform at 5.0 Hz. These results demonstrate that loading condition affects the strain energy per cycle at the same stress level. This is because the deformation behavior of plywood specimens at the same stress level depends on loading condition, as shown in Fig. 4.

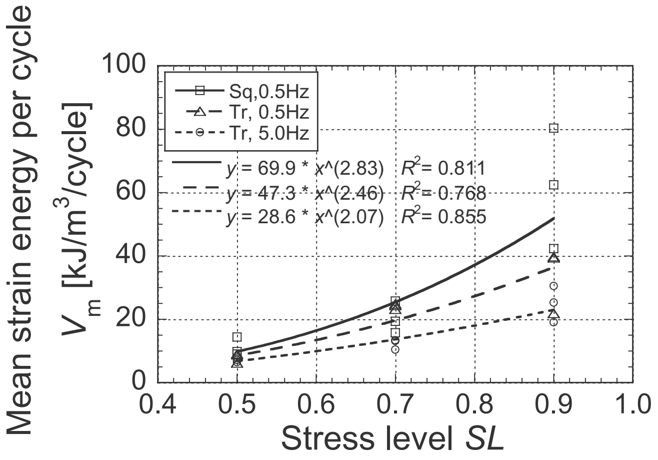

Fig. 6. Relationship between mean strain energy per cycle (V_m) and stress level (SL) for all specimens in fatigue test

The relationship between mean strain energy per cycle (V_m) and stress level (SL) is shown in Fig. 6. Mean strain energy per cycle varied with loading condition at higher stress levels. At each stress level, strain energy per cycle decreased in the order of the square waveform at 0.5 Hz, the triangular waveform at 0.5 Hz, and the triangular waveform at 5.0 Hz. The fatigue life of the plywood specimen at each stress level became longer in the same order, as shown in Fig. 3. Therefore, it is likely that the fatigue life of the plywood specimen is dependent on mean strain energy per cycle.

Figure 7 shows the relationship between mean strain energy per cycle (V_m) and fatigue life (N_f) for all the specimens tested in the fatigue test. Fatigue life obtained under different loading conditions was found to be almost the same at a certain value of mean strain energy per cycle, and lengthened in the same manner when mean strain energy per cycle decreased. Therefore, the relationship between mean strain energy per cycle and fatigue life is independent of loading condition. Furthermore, mean strain energy per cycle seems to gradually approach a fixed value as fatigue life lengthens. Fatigue life will be infinite in the case that the mean strain energy per cycle is below the fixed value. Then the fixed value of mean strain energy per cycle is considered to be the threshold determining whether the test specimen is damaged by one loading cycle, that is, the fatigue limit of the plywood specimen in terms of strain energy. The fatigue limit of wood-based panels may be useful in designing timber structures, and hence is analyzed below.

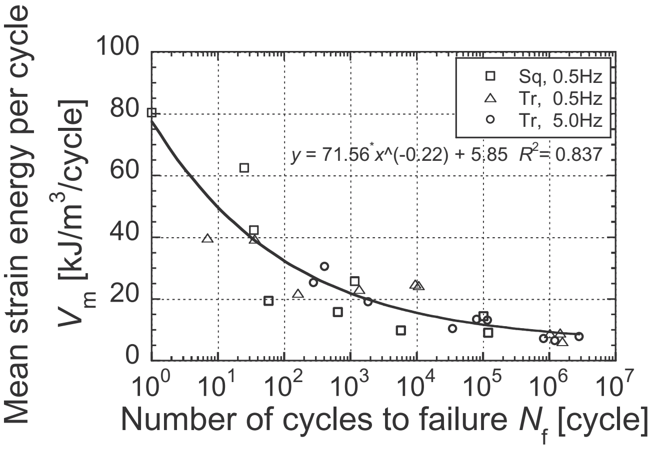

Fig. 7. Relationship between mean strain energy per cycle (V_m) and number of loading cycles to failure (N_f) for all specimens in fatigue test

To obtain the threshold value of mean strain energy per cycle, the following equation between mean energy loss per cycle (V_m) and fatigue life (N_f) was fitted to the data shown in Fig. 7:

$$V_m = aN_f^{-b} + c \qquad (1)$$

where a, b, and c are positive constant coefficients. Coefficient c is the threshold value of mean strain energy per cycle because the first term in Eq. 1 is asymptotically zero when the fatigue life is infinite. The c value was calculated to be 5.85 kJ/m^3 per cycle, as shown in Fig. 7. This result suggests that plywood specimens probably remain undamaged by cyclic shear load through the thickness, which generates a mean strain energy per cycle below the threshold value under any of the loading conditions.

Cumulative strain energy during fatigue

The change in cumulative strain energy at the N^{th} loading cycle (V_{ac}) is shown in Fig. 8. Figure 8a shows the results for square and triangular waveforms at the loading frequency of 0.5 Hz, while Fig. 8b shows those for the triangular waveform at 0.5 Hz and 5.0 Hz. A typical example is shown at each stress level under the respective loading conditions. Cumulative strain energy increased linearly with the number of loading cycles (N) on a logarithmic scale under all the loading conditions. Therefore, the fatigue process of plywood specimens could be independent of loading conditions on the assumption that the accumulation of strain energy is an index of fatigue progression. Log–linear regression was then conducted for the data for each specimen using:

$$V_{ac} = aN^b \qquad (2)$$

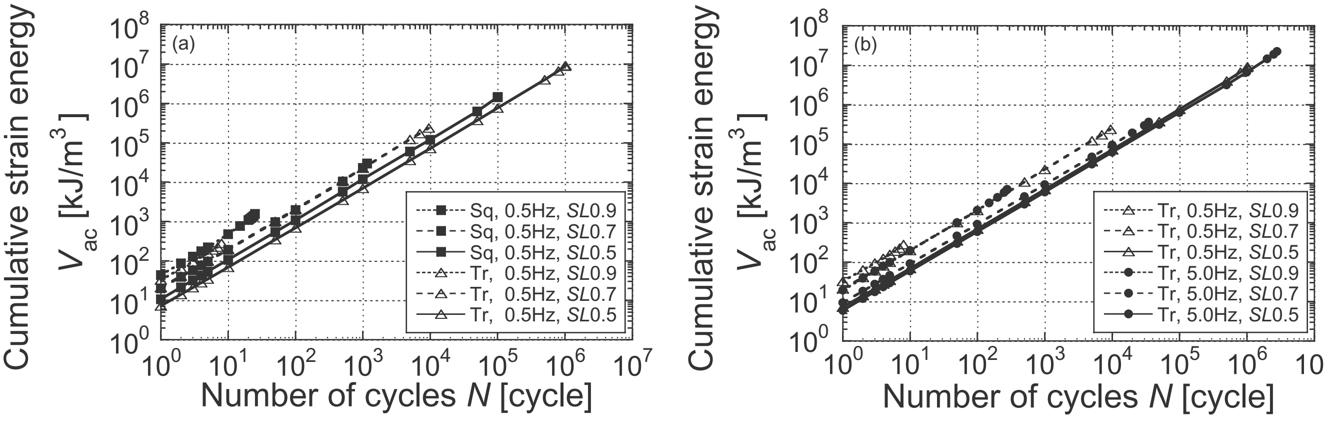

Fig. 8a, b. Typical fatigue-related change in cumulative strain energy (V_{ac}). **a** Square waveform at loading frequency of 0.5 Hz and triangular waveform at the same frequency, and **b** triangular waveform at 0.5 Hz and 5 Hz

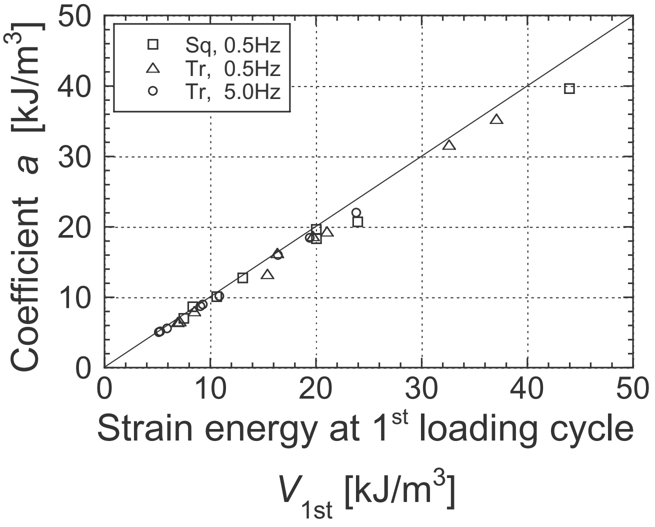

Fig. 9. Relationship between regression coefficient a in Eq. 2 and strain energy at first loading cycle (V_{1st}) for all specimens in fatigue test

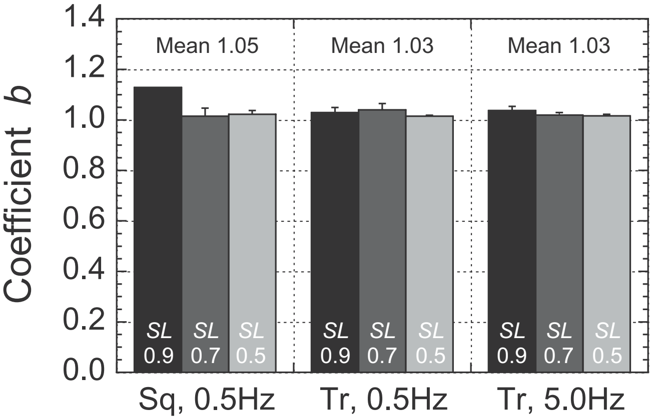

Fig. 10. Regression coefficient b in Eq. 2. Each column shows mean ± standard deviation for three specimens

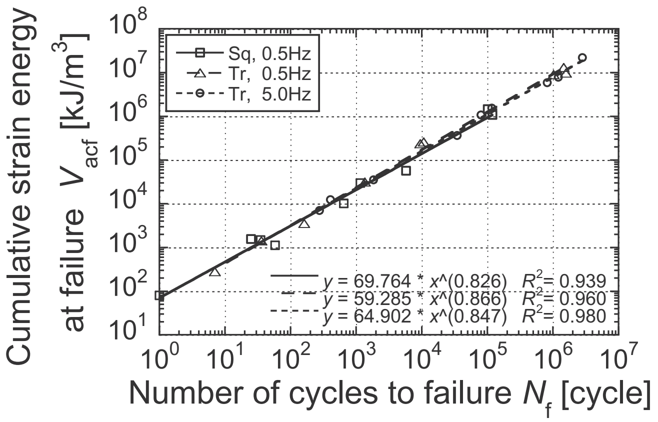

Fig. 11. Relationship between cumulative strain energy at failure (V_{acf}) and fatigue life (N_f) for all specimens in fatigue test

where a and b are positive constant coefficients. The regression analyses showed that the coefficients of determination (R^2) were above 0.98 for all the specimens. The relationship between the a value obtained and the strain energy at the first loading cycle for all specimens in the fatigue test is shown in Fig. 9. This figure shows that the strain energy at the first loading cycle is considered to be almost equal to a for every specimen. The b values were found to be almost the same under all loading conditions, although the value for the square waveform, the loading frequency of 0.5 Hz, and the stress level of 0.9 was slightly greater than the others (Fig. 10). This is because the peak stress applied during most of the loading phase generated the characteristic stress–strain curve in the square waveform, as shown in Fig. 4. The mean ± standard deviation of b for all specimens was 1.03 ± 0.03. These results indicate that the fatigue process of plywood specimens under various loading conditions is commonly expressed by:

$$V_{ac} = V_{1st} N^{1.03} \tag{3}$$

where V_{1st} is the strain energy at the first loading cycle, and N is the number of loading cycles. When the strain energy at the first loading cycle (V_{1st}) of a test specimen is obtained under any of the loading conditions, its fatigue process can be expressed by Eq. 3. The strain energy at the first loading cycle (V_{1st}) of a test specimen is obtained by only the first cycle loading test under any loading conditions, which is conducted as easily as the static test.

Equation 3 expresses the common fatigue process of plywood specimens in terms of strain energy for various loading conditions. The fatigue failure behavior of the specimens is discussed in the next section.

Cumulative strain energy at fatigue failure

The relationship between cumulative strain energy at failure (V_{acf}) and fatigue life (N_f) is shown in Fig. 11. A log linear relationship was observed for each loading condition, and the relationships were almost the same irrespective of loading condition. The regression line for all the loading conditions was obtained as

$$V_{acf} = 62.875 N_f^{0.851} \ (R^2 = 0.974) \tag{4}$$

These results suggest that the relationship between cumulative strain energy at failure and fatigue life is independent of the loading condition. Therefore, this relationship is considered to be the fatigue failure criterion of the plywood specimen under various loading conditions in cyclic shear through the thickness. It is very significant to successfully express the unique failure criterion of fatigue under various loading conditions by analyses based on strain energy. These strain energy analyses could be applicable to study the fatigue of solid wood and wood composites under other loading modes such as tension, compression, and bending with various loading profiles. We speculate that the analyses performed in this study contribute to the elucidation of the damage development and failure mechanism of wood and wood composites.

Conclusions

Strain energy analyses provided experimental equations of the fatigue process and the failure criterion of plywood specimens, which could be commonly applied to various loading conditions. Mean strain energy per cycle for the fatigue limit was calculated to be 5.85 kJ/m^3 per cycle, which is independent of the loading condition.

In Part 2 of this study, a new method for predicting fatigue life will be proposed and discussed on the basis of the fatigue process and the failure criterion of plywood specimen under cyclic shear through the thickness elucidated in this article.

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