Fracture Behavior of Laminated Wood Bonded with Water Based Polymer-Isocyanate Resin and Resorcinol-Formaldehyde Resin Under Impact Fatigue

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ABSTRACT: The impact fatigue behavior of laminated wood bonded with water based polymer-isocyanate resin (WPI) and resorcinol–formaldehyde resin (RF) was investigated. The number of cyclic blows to failure (N_b) for laminated wood was lower than that for solid wood. For laminated wood, N_b showed a significant decrease with an increase in temperature, while for solid wood, it showed a slight decrease. The fatigue life of laminated wood bonded with WPI was lower than that of RF. For laminated wood bonded with WPI, the ratio of the height of rebound (Q_n) to that of the first rise (P_n), which was evaluated from an impact stress wave, remained constant and then gradually decreased before failure. This indicates that the energy consumed by heating increased before failure because the cured WPI has viscosity. For RF, Q_n/P_n remained constant immediately before failure because cured RF is rigid. At a lower test temperature, the fracture surface almost entirely comprised the wood. As the temperature increased, the laminated wood fractured predominately in the adhesive layer. This could be attributed to a decrease in the rigidities of WPI and RF. The impact fatigue behavior of laminated wood is related to the mechanical properties of the adhesives. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 109: 276–281, 2008

Key words: impact fatigue failure; laminated wood; adhesives; viscoelastic properties

INTRODUCTION

Glued laminated timber is used as a construction member in many applications including floor beams, roof beams, columns, decks, and girders. In some cases, these materials are exposed to repeated impact loading.

Repeated loads may damage these materials even if the applied energy levels are below those necessary to cause fracture in a single load. The development of the damage under cyclic fatigue loads may lead to the final catastrophic failure of the component. Taking this into consideration, the fatigue behavior of laminated wood has been discussed in a number of papers. Nagasawa et al.[1] have studied the bending fatigue behavior of the adhesive joints of laminated wood. They found that the strength of the fatigue limit of an adhesive joint was 1/5 to 1/3 times its static bending strength. Further, the bending fatigue behavior of adhesive joints was reflected in the mechanical properties of adhesives when the deflection magnitude was larger than that at the proportional limit.[2] A rapid increase in temperature and a decrease in dynamic stress were observed in wood and laminated wood during the fatigue process when cyclic nonlinear deflections were applied to a cantilever bend.[3–5]

The impact resistance of glued laminated timber is also a very important property in engineering applications because wood members fail more frequently under the influence of impact stresses than under static overloading in building construction.[6] It is well known that adhesive strength changes drastically with an increase in the rate of strain including impact load. Hatano and Mizumachi.[7] calculated the values of adhesive shear strength theoretically as a function of the rate of deformation, according to the mechanical model proposed by Hata.[8] They stated that there is a need to clarify the physical significance of a criterion for an abrupt transition of failure modes from cohesive failure to interfacial failure. Imanaka et al.[9] found that stress concentrations caused a greater reduction in the impact fatigue strength of an adhesive joint than in the nonimpact fatigue strength of a steel plate bonded with an epoxy-polyamide adhesive. Sakuno and Goto.[10] found that the defects of a glued joint (such as a starved joint) caused a greater reduction in the impact shear strength than in the static shear strength of glued wood. The impact fatigue behavior of laminated wood, however, has not been reported.

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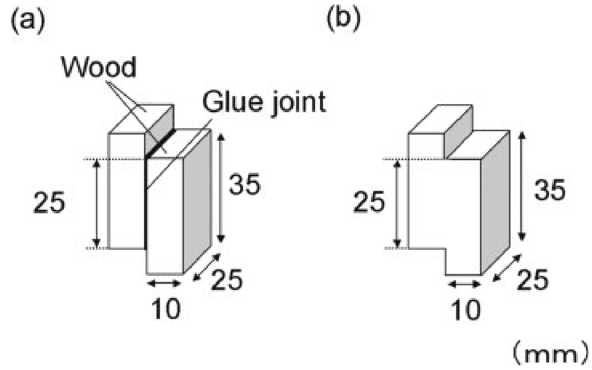

Figure 1 Block shear specimens for (a) laminated wood and (b) solid wood.

In this study, we evaluated the impact fatigue behavior of adhesive joints of laminated wood bonded with water based polymer-isocyanate resin (WPI) and resorcinol–formaldehyde resin (RF). These resins are utilized as adhesives for glued laminated timber, which is used as a structural element. We carried out impact fatigue tests at various temperatures. Furthermore, we examined the influence of the viscoelasticity of adhesives on the impact fatigue behavior.

EXPERIMENTAL

Materials

The adhesives used in this work are WPI (KR-120R, Koyo Sangyo (Tokyo, Japan)) and RF (Phenolite 6000, Dainippon Ink and Chemicals (Tokyo, Japan)). WPI consists of polyvinyl alcohol (PVA) and styrene-butadiene rubber (SBR) latex and RF consists of resorcinol and its condensates. WPI was cured by adding a hardener (AG, Koyo Sangyo (Tokyo, Japan)), which consists of 4,4-diphenylmethane diisocyanate (MDI) and polymeric MDI. The hardener added to RF (TD-475, Dainippon Ink and Chemicals (Tokyo, Japan)) consists of paraformaldehyde and wood flour.

Japanese ash (*Fraxinus mandshurica* Rupr.) was used as an adherend. The specimens were conditioned to the equilibrium moisture content in a chamber maintained at 20°C and 65% RH. The moisture content of the specimens was ~12%, and it was determined by weighing the loss in mass of the test piece on drying at 105°C to a constant mass.[11]

Impact fatigue test

Each laminated assembly was constructed from two pieces of lumber having dimensions of 300 (L) × 100 (R) × 10 (T) mm, where L, R, and T are the longitudinal, radial, and tangential directions, respectively. The wood surface to be bonded was planed and coated with 250 g/m^2 of the adhesives. The laminas were quickly jointed together, and then the two-ply lumber laminates were cured under a pressure of 1.5 MPa for 24 h at 20°C and 65% RH. These samples were stored at 20°C and 65% RH. They were cut into specimens for the compression block shear test [Fig. 1(a)]. Solid wood was also cut into specimens, as shown in Figure 1(b).

Figure 2 shows the apparatus used for the impact fatigue test. The compression block shear specimens were loaded by the impact of a falling body. The weight of the falling body was 254 g, the height of the drop was 48 cm, and the speed with which the striker contacted the specimen was 1.9 × 10^5 mm/min. An accelerometer placed on the striker was connected to an oscilloscope, which recorded and stored waveforms. The waveform data were transferred to a microcomputer. In the repeated-blow impact test, the falling body struck a test specimen every 7 s until complete failure of the specimen was observed. The impact fatigue test was carried out at temperatures ranging from 25 to 65°C. Five specimens were tested for each test temperature.

Dynamic viscoelastic measurement by torsional braid analysis

A mixture containing 13 wt % hardener and 87 wt % base polymer was prepared for RF and WPI. Fiberglass braids were immersed in the mixture and then cured at room temperature. The sample was dried under vacuum at room temperature with phosphorus pentoxide for 1 day and then subjected to torsional braid analysis (TBA) measurement. TBA measurements were carried out using a Rhesca RD-1100AD (Tokyo, Japan). The temperature was controlled at a heating rate of 2°C/min from –100 to

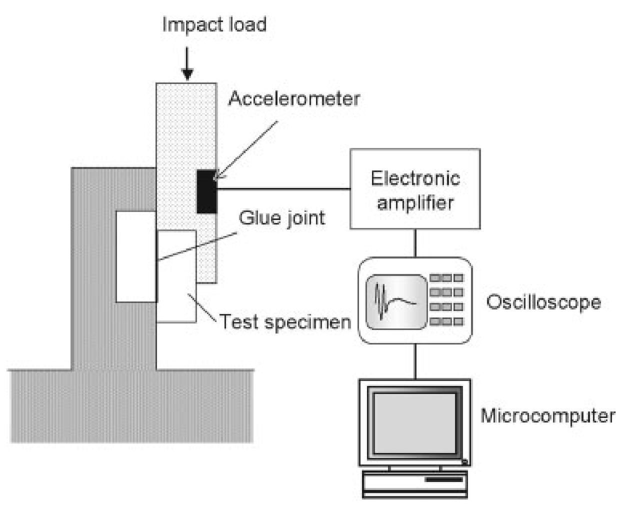

Figure 2 Schematic of repeated impact tests.

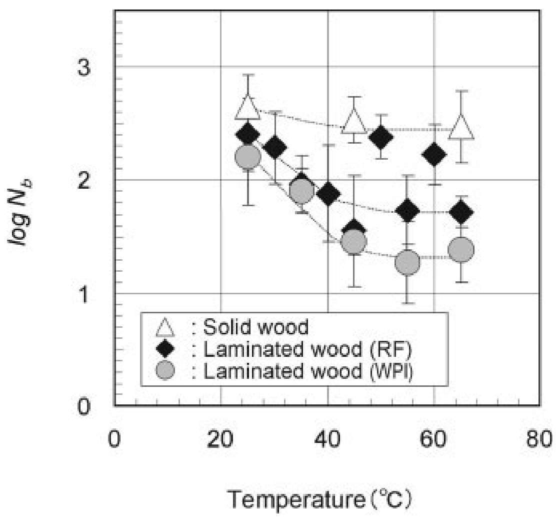

Figure 3 Number of cyclic blows to failure (N_b) versus temperature for laminated wood and solid wood.

180°C under vacuum. The frequency of oscillation was about 0.1 Hz.

RESULTS AND DISCUSSION

Fatigue life under cyclic impact loading

Figure 3 shows a plot of the common logarithm of the number of cycles to failure, log $N_{b,}$ versus the test temperature. The number of cycles to failure of the laminated wood was lower than that of the solid wood. However, the static shear strength of laminated wood bonded with RF and WPI was not lower than that of solid wood. It was reported that the impact fatigue strength of a lap-joint specimen decreased more rapidly than the nonimpact fatigue strength with an increase in the stress concentration factor.[9] This implies that adhesive layers are sensitive to impact loading.

As the test temperature increased, N_b of the laminated wood showed a significant decrease, while that for the solid wood showed a slight decrease. The fatigue life of the laminated wood was affected by the test temperature. Furthermore, it was found that N_b for WPI was lower than that for RF. The difference between N_b of RF and WPI increased with the test temperature.

Impact response of laminated wood

Figure 4 shows typical impact waveforms obtained by a blow on laminated wood bonded with WPI at 65°C. Similar waveforms were observed in the results of laminated wood and solid wood at all the temperatures at which the fatigue failure tests were performed in this study.

Three types of impact waves were observed, and we could divide the fatigue damage process into three stages. In the first stage, a damped frequency curve, as shown in Figure 4(a), was observed. Such a damped frequency curve was observed in tensile impact tests on wood[12] and lap-jointed wood bonded with phenol resin.[13] In the second stage, the rebound decreased [Fig. 4(b)], which was observed before failure. In the final stage, the rebound disappeared [Fig. 4(c)].

The initial increase in the shear stress is related to the energy provided by a blow; the subsequent rebound is related to the energy released by internal damping. Some part of the applied energy is released by internal damping, while the remaining part contributes to irreversible changes, including heating, crack initiation, and crack growth. The impact stress wave that appeared in the first stage [Fig. 4(a)] indicates that most of the applied energy is released by internal damping and a small part of the energy is consumed by irreversible changes. Jakusik et al.[14] determined that a part of the applied energy was absorbed irreversibly by the specimen in the repeated impact test for rubber-modified epoxy resin. Repeated loading will contribute to crack initiation and crack growth in materials. Further, the elasticity and damping of materials will change. Such an irreversible change gradually accumulates

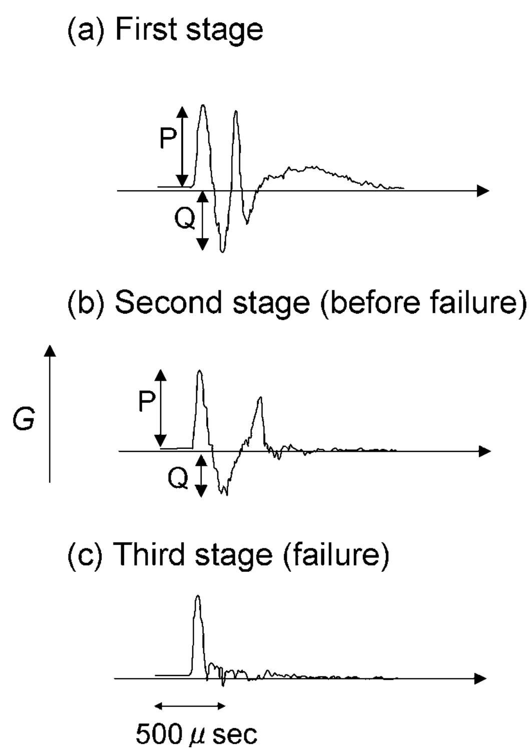

Figure 4 Typical plot of shear stress versus time based on cyclic blows at 65°C for laminated wood bonded with WPI.

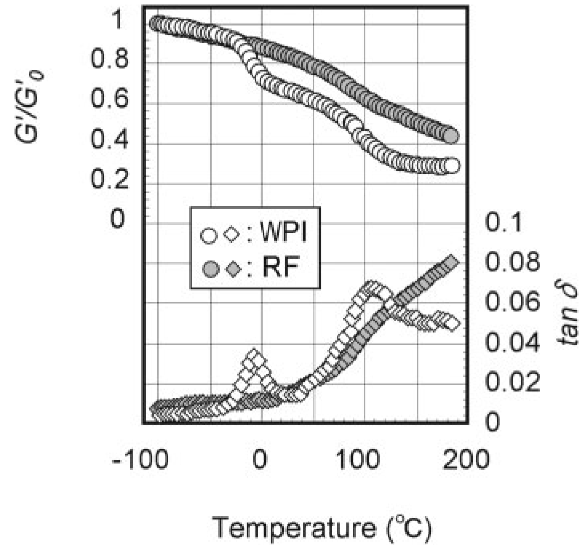

Figure 5 Temperature dependence of relative rigidity G'/G'_0 and loss tangent tan δ for cured WPI and RF.

in this stage. Subsequently, the energy released by internal damping decreased before failure, as shown in Figure 4(b). Finally, complete fracture occurred [Fig. 4(c)].

The nonlinear stress-strain curves exhibit cyclic hysteresis. It is known that the area within the loop represents the energy consumed by internal friction during one loading–unloading cycle.[15] For adhesive joints, the number of cycles to failure under cyclic loading was proportional to the cube root of the logarithmic decrement of the adhesives, $\lambda^{1/3}$.[15,16] Hence, we examined the viscoelastic properties of RF and WPI and the influence of the adhesive viscoelasticity on the impact fatigue behavior of laminated wood.

Dynamic viscoelastic properties of cured RF and WPI

Figure 5 shows the dynamic viscoelastic properties of RF and WPI used in the impact fatigue test of laminated wood. For cured RF, the loss tangent (tan δ) increased and the relative rigidity (G'/G'_0) decreased moderately, indicating that the mobility of its chains was restricted and the cured resins were rigid. For cured WPI, the plot of tan δ clearly exhibited temperature dispersions localized approximately –10 and 110°C. At these temperatures, G'/G'_0 significantly decreased. These observations are caused by the relaxation of the constituents in WPI. The first peak at –10°C and the second peak at 110°C are attributed to the relaxation of the SBR chains and the PVA chains, respectively. These results indicate that cured WPI is comparatively flexible, while cured RF is rigid.

Fatigue behavior before failure

The ratio of the height of rebound (Q_n; subscript n is the number of repeated blows) to that of the first rise (P_n) was evaluated from a damped frequency curve (Fig. 4). Figure 6 shows the relationships between Q_n/P_n, which is related to the ratio of the energy absorbed by internal damping to the energy applied by impact loading, and the number of cyclic blows at 25°C. The height of the first rise by the nth cycle of blows (P_n) remained constant during the impact fatigue tests ($P_n = P_1$) for solid wood and laminated wood bonded with RF and WPI. There-

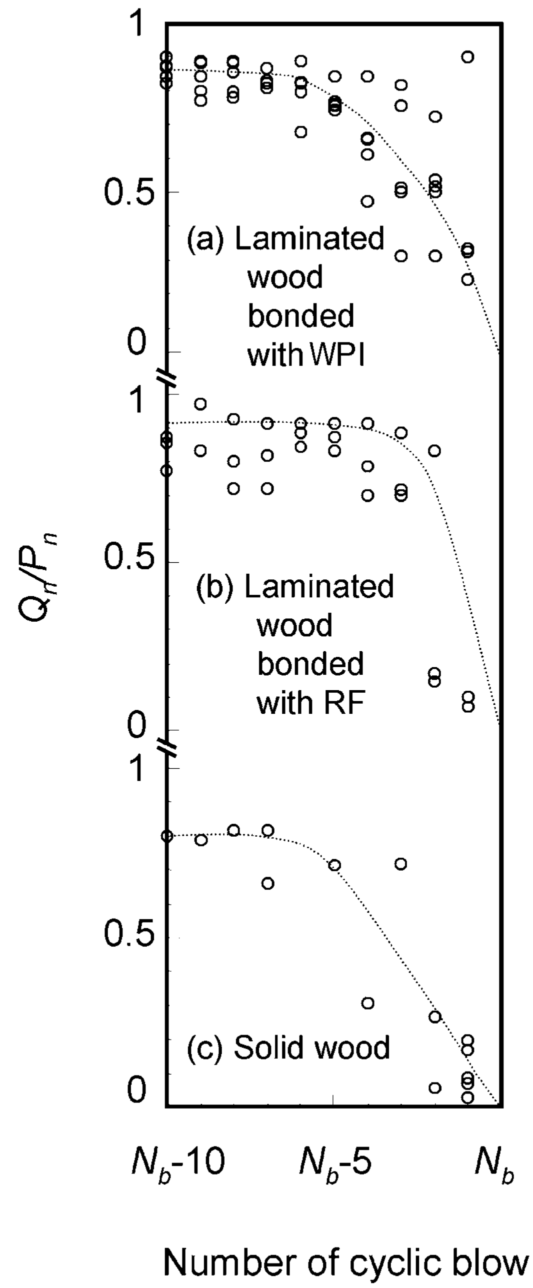

Figure 6 Wave height ratios Q_n/P_n versus the number of cyclic blows at 25°C.

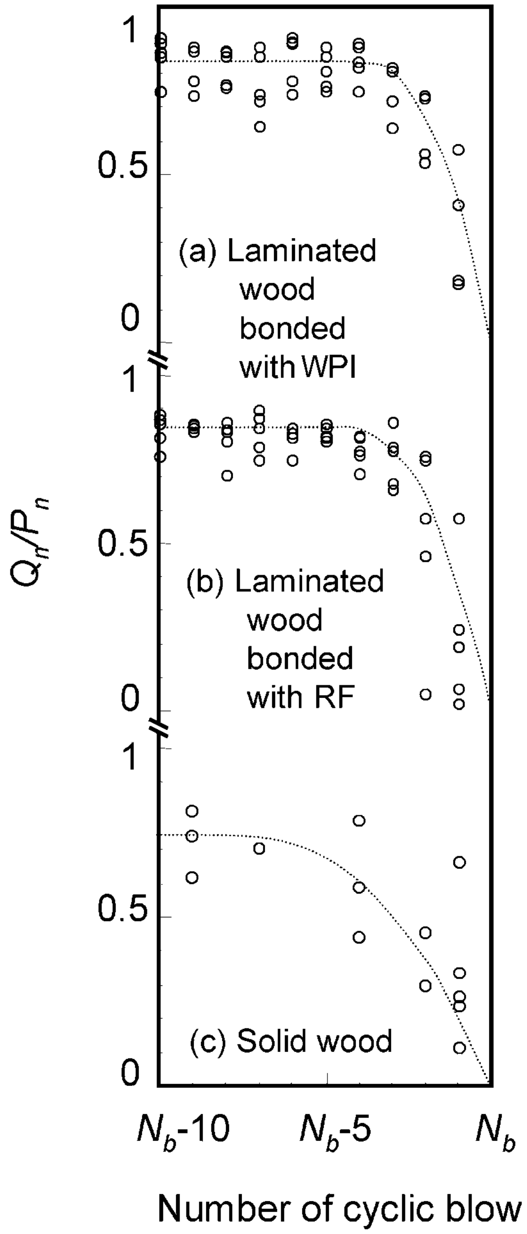

Figure 7 Wave height ratios Q_n/P_n versus the number of cyclic blows at 45°C.

fore, P_n is independent of the number of blows. Q_n/P_n was constant several times before causing failure for all the specimens used in this study. In Figures 6 and 7, therefore, the number of blows is shown from N_{b-10} (10 times before causing failure) to N_b.

For laminated wood bonded with WPI, Q_n/P_n remained constant until N_{b-5} and then gradually decreased [Fig. 6(a)]. This indicates that the energy released by internal damping gradually decreased and that consumed by irreversible changes gradually increased before failure. A similar behavior was found in the Q_n/P_n for solid wood, as shown in Figure 6(c). On the other hand, the Q_n/P_n for laminated wood bonded with RF remained constant immediately before failure [Fig. 6(b)].

Cyclic deflections increase the temperature of the test specimens by heating due to the specimen viscosity.[3–5] Cyclic blows will also increase the temperature of the test specimens. The difference between the decrease in Q_n/P_n before failure for laminated wood bonded with WPI and that bonded with RF can be described as follows. The molecular mobility of WPI becomes more vigorous, since the temperature of specimen increases due to cyclic blows. As the molecular mobility increases, more energy is converted into heat. This leads to a decrease in Q_n/P_n before failure. Solid wood also has a particular viscosity and can be considered to exhibit a similar behavior.

Cured RF has low viscosity (Fig. 5). The molecular mobility is still limited when repeated blows increase the temperature of the specimens. However, the quantity of energy converted into heat does not increase. Thus, specimen failure occurred without a gradual decrease in Q_n/P_n.

When the test temperature increased to 45°C, Q_n/P_n for laminated wood bonded with WPI remained constant immediately before failure (Fig. 7). The $Q_n/$

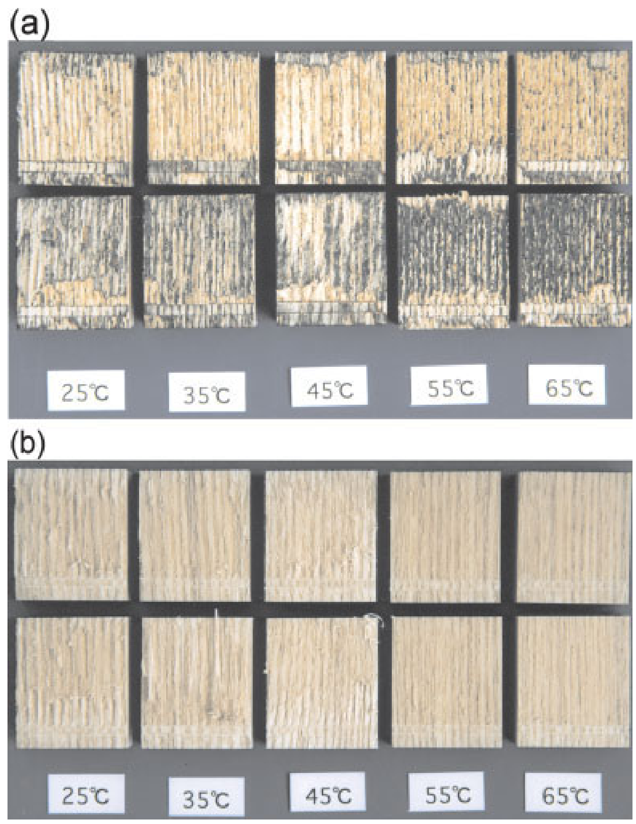

Figure 8 Typical fracture surface for laminated wood bonded with (a) RF and (b) WPI. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

P_n curves at 45°C did not indicate a gradual decrease in the energy absorbed by internal damping before failure. The average N_b for laminated wood bonded with WPI at 45°C was only 30, while that at 25°C was over 200 (Fig. 3). It is assumed that laminated wood bonded with WPI fractured before the amount of energy consumed by heating increased. Similar curves were observed in the impact fatigue tests conducted at 55 and 65°C.

On the other hand, for the laminated wood bonded with RF, the Q_n/P_n curves at 45°C remained constant immediately before failure (Fig. 7). There is little or no difference in the curves at 25–65°C since the molecular mobility of cured RF is restricted at these temperatures, as shown in Figure 5.

The Q_n/P_n curves at 25–65°C for solid wood show a decrease in the energy released by internal damping before failure. The test temperature does not affect the resistance to impact fatigue failure for solid wood.

Fracture surface of laminated wood

Figure 8 (a) shows the fracture surface of laminated wood specimens bonded with RF after the cyclic impact fatigue test. Wood is indicated by the light-colored areas, while the RF adhesive is indicated by dark-colored areas. The fracture surface almost entirely comprised the wood section at 25°C. As the test temperature increased, the light-colored areas decreased and the dark-colored areas increased. This indicates that laminated wood bonded with RF fractured predominately in the wood section at a lower temperature and in the adhesive layer at a higher temperature. In the case of laminated wood bonded with WPI, as shown in Figure 8(b), the fracture surface almost entirely comprised the wood section at 25°C. As the test temperature increased, the fracture surface became smooth. This indicated that laminated wood bonded with WPI fractured predominately in the adhesive layer at higher temperatures.

At a lower test temperature, the laminated wood failed mostly in the wood section and its impact fatigue life was slightly shorter than that of solid wood. As the test temperature increased, the failure of the laminated wood occurred mostly in adhesive layer and the fatigue life was shortened. The relative rigidity of WPI and RF decreased with an increase in temperature (Fig. 5). The decrease in the impact fatigue life of laminated wood can be attributed to a decrease in the cohesive strength of the adhesives.

CONCLUSIONS

The number of cyclic blows to cause failure, N_b, was lower for laminated wood than for solid wood. Furthermore, N_b for laminated wood showed a significant decrease with an increase in temperature, while that for solid wood showed a slight decrease. The ratio Q_n/P_n, which is related to the ratio of energy absorbed by internal damping to the energy applied by impact loading, reflected the impact response of the specimens. For laminated wood bonded with WPI, Q_n/P_n remained constant and then decreased gradually; this was followed by failure. This feature indicated that the energy consumed by heating increased gradually before failure. For laminated wood bonded with RF, Q_n/P_n remained constant immediately before failure and did not show such a gradual decrease. As the temperature increased, the fracture surface of the laminated wood changed from the wood to the adhesive layer. It can be seen that the cohesive strength of adhesives decreased due to a decrease in their rigidities. The fatigue behaviors under cyclic blows of the laminated wood bonded with RF and WPI were reflected in the viscoelastic properties of the adhesives.

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