High-speed bending-fatigue testing of composite materials

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Abstract. A methodology for high-speed fatigue testing, especially for resin materials, including fibre-reinforced composites, was devised and evaluated. To exert periodic stress on a material at a frequency of more than 200 Hz, a specimen (made of glass fibre-epoxy laminate) was fixed as a cantilever to an electromagnetic vibrator and vibrated at its resonant frequency of the first bending mode by using a resonance tracking control. The shape of the specimen was designed with finite-element vibration analysis to obtain a resonant frequency of more than 200 Hz and a desired strain distribution for inducing fatigue damage under a certain stress level. The rise in temperature during the fatigue testing (due to damping loss) was estimated by applying heat-transfer theory and suppressed by external cooling to keep the specimen at room temperature. To confirm the validity of the devised high-speed-testing method, a completely reversed bending test at 1 Hz was also performed with identical specimens. The results from both testing methods (conducted at 230 Hz and 1 Hz, respectively) were plotted on a single power-law curve in an S-N plot. The good agreement between the two plots suggests that fatigue strength in the high- or giga-cycle region of resin and composites can be evaluated in a very short time if temperature is controlled appropriately.

1. Introduction

The range of applications of resin materials in industrial products is expanding year by year. Especially, fibre-reinforced composite (FRC)—combining carbon fibres and glass fibres as reinforcing materials—is excellent in terms of specific strength and specific stiffness, so it is increasingly used for transportation equipment such as cars and aircraft, which are required to be lightweight and highly reliable. Also, in the field of power production, FRC is applied for the main-load carrying member of rotor blades of wind turbines.

It is expected that the number of cases in which resin or FRC materials are adopted as structural members of industrial products will increase in the future. Resins and FRC materials to be evaluated are also becoming more diverse, and the choices for selecting FRC materials are increasing exponentially. On the other hand, it is known that the material properties of the resin depend on slight differences in composition, presence or absence of additives, curing conditions and the like. It is therefore necessary to sufficiently understand the characteristics of individual materials for designing reliable structures or products. If the reliability parameter is the static strength, it can be evaluated in a relatively short period of time. However, evaluating fatigue strength, which usually takes a very long period of time, is required when products are to be used under dynamic loading conditions. Therefore, fatigue testing sometimes becomes a bottleneck in the product-development process. For example, when a fatigue strength evaluation of $10^7$ cycles is required, execution of a single test may require a long time (more than a month) since the test speed of a general fatigue-testing machine is at most about several 10 Hz. In recent
years, the number of products, such as rotor blades of wind turbines, requiring a fatigue design that assumes dynamic loading exceeding $10^7$ cycles is increasing. In light of those circumstances, a faster fatigue-test method applicable to resin and FRC materials is desired. Some fatigue-testing machines can actually attain a test speed exceeding 100 Hz; however, under the assumption large-size blades for mega-watt-class wind-power generators, etc., the repetition frequency of the load fluctuation achieved by the testing machine is actually in the order of several hertz [1]. When higher frequency is applied for shortening the testing time, it is important to verify the influence of the difference between the test frequency and the actual machine frequency on the result carefully. In particular, if the resin material is visco-elastic, heat generation due to viscous loss occurs as the test frequency is becoming higher, so it is considered that this will cause a difference from the test result under normal temperature. Regarding the relationship between fatigue-damage behaviour of the resin material and test frequency, although the frequency range is limited to several dozen hertz, several reports have been made [2-4]. However, a unified view has not been obtained, and there are many unknowns about fatigue-damage behaviour of the resin and FRC materials exposed to high-frequency loading.

One of the reasons for this state of affairs is that it is difficult to conduct a fatigue test under independently controlled specimen temperature and test frequency. Another reason is that it is practically difficult to attain both a higher test frequency together and a large deformation that are necessary for testing a resin material.

A carbon-fibre-reinforced (CFR) composite material was fatigue tested under a uniaxial tensile mode (stress ratio $R = 0.1$) at a test speed of 100 Hz by Hosoi et al. [5]. Under the assumption that the test did not cause significant heat generation, the test result is considered equivalent to a result obtained at 5 Hz. However, in their test, CFR resin was targeted because it has excellent heat conductivity, and a relatively thin test piece was used. Consequently, it was easy to suppress the temperature rise of the test piece even if the test is performed at high frequency. It was also easy to obtain a uniform temperature distribution in the cross-sectional direction. Despite those achievements, it is required to devise a novel test method applicable to a broader range of materials and specimen sizes and a higher testing frequency. In the present study, therefore, a test frequency of 200 Hz (at which a fatigue test of $10^7$ cycles is completed in about half a day) is targeted, and a test method that can induce planar bending at high speed by using the resonance of the specimen is proposed [6]. The proposed method was applied to a general-purpose epoxy glass laminate, and the influence of test frequency and test-piece temperature on fatigue life was investigated.

2. Materials and Methods

2.1. Resonant bending-fatigue testing system

A schematic diagram of the test system developed for a resonance bending fatigue test (hereinafter referred to as “high-speed fatigue test”) is shown in Figure 1. The fixed end of the cantilevered-beam specimen is attached to a vibrating head of an electromagnetic vibrator (i210/SA03, IMV, Japan). By subjecting the specimen to resonance at its natural frequency, large deformation can be generated in the specimen with comparatively little exciting force. Furthermore, control logic was applied to maintain the resonance condition of the specimen. That is, a small acceleration sensor (353C23, PCB, USA) for measuring response acceleration is attached to the free end of the specimen, and the phase difference between the excitation acceleration at the fixed end and the response acceleration at the free end is kept at 90° by this control logic. Since the stiffness of the test specimen fluctuates due to fatigue damage and temperature change during the fatigue test, the natural frequency changes moment by moment. However, this control logic maintains the resonant state of the specimen under stiffness fluctuation during the fatigue test. Bending strain and specimen temperature during the test were measured with a strain gauge and a T-thermocouple attached to the specimen, respectively. Amplitude of acceleration, strain, specimen temperature, and natural frequency during the test were recorded as time-history data by using a data logger (NR 500, Keyence, Japan) with a data acquisition rate of 1 Hz. The vibrating head of the
electromagnetic exciter (including the test specimen) was installed in a thermostat chamber so that the ambient temperature could be arbitrarily controlled.

![Diagram](image)

**Figure 1.** Schematic experimental setup for high-speed fatigue test [6].

### 2.2. Characteristics of materials

In the present study, which aimed to investigate the applicability of the high-speed fatigue test to composite materials, a general-purpose epoxy/glass-cloth laminate was used as a model material for evaluation. Its specifications and characteristics are listed in Table 1.

| Specification                  | Value               |
|-------------------------------|---------------------|
| Type                          | JIS-K6912, EL-GEM   |
| Matrix resin                  | Epoxy               |
| Reinforcement                 | Plain-woven glass fabric [0/90] |
| Thickness                     | 3 mm                |
| Specific weight               | 1.85 g/cm³          |
| Bending elastic modulus       | 22.6 GPa            |
| Bending strength              | 420 MPa             |
| Heat conductivity             | 0.471 W/m·K         |

### 2.3. Characteristics of test specimen

A test frequency of 200 Hz or higher was set as the target. The approximate specimen geometry was determined by assuming a cantilever beam with a uniform rectangular cross section, and the natural frequency was determined as

\[ f = \frac{\lambda^2}{2\pi L^2} \sqrt{\frac{EI}{\rho A}} \]  

where \( L \) is specimen length, \( E \) is elastic modulus, \( I \) is the second moment of area, \( \rho \) is density, and \( A \) is cross-sectional area. Parameter \( \lambda \) is 1.875 in the case of the first-order mode of the cantilever beam. Here, the dimensions of the test specimen (70×15×3 mm), with a natural frequency of 500 Hz or more (which is sufficiently higher than the target frequency of 200 Hz) were temporarily determined.
The optimum specimen shape, having the strain distribution shown in Figure 4, was determined by frequency-response analysis based on the finite element method in consideration of the attachment to the shaker, the method of adjusting the natural frequency, and the strain distribution in the specimen as follows. In the high-speed fatigue test, the specimen is gripped in a cantilevered manner and vibrated through its resonance state. Therefore, a fixed part is created on the fixed-end side, and a weight-attachment part (for adjusting natural frequency) is created on the free end. As shown in Figure 1, the specimen is attached to the electromagnetic vibrator via the fixing jig. Thus, in the fixed end, the local stress distribution will be spatially steep depending on the contact state between the fixing jig and the test piece. To overcome this non-ideal stress-distribution state, the test piece was formed as a fillet shape (namely, its width decreases sharply from the fixed end to the free end) so that maximum stress occurs at a position about 17 mm away from the fixed end. Adapting this shape has the advantage that mounting a sensor such as a strain gauge or a thermocouple becomes easy at the position where maximum stress is generated. For the determined specimen shape, bending-strain distribution was evaluated by frequency-response analysis based on the finite-element method. For the analysis, a general analysis environment, namely, ANSYS Workbench 14.0 (ANSYS), was used. In this analysis, it was aimed to evaluate the relative strain distribution in the test piece, so it was not necessary to acquire the absolute value. Therefore, the damping ratio was temporarily set as 1%. Displacement of the fixed part of the specimen was completely constrained, and the acceleration sensor and weight (including mounting bolt, washers, and nuts) on the free end were modelled as lumped masses at each barycentric position.

The bending-strain distribution in the longitudinal direction of the specimen obtained by the above-described analysis is shown in Figure 3 and Figure 4. The value of the bending strain was expressed as a relative value in regard to the strain at the position of the maximum generated bending stress. The natural frequency is an approximate number because it has an error of about 7% at the maximum between the measured value and the value predicted by the analysis. Since the deformation mode changes due to the mass of the weight mounted on the free end, it was a concern that the strain distribution would change as well. However, the strain distribution did not significantly change, and the deviation of the maximum-strain position to be evaluated was 1 mm or less. Even if a position 1 mm away from the maximum strain position was applied in the evaluation, the error of the strain under that condition would be 1% or less. Therefore, the difference between these deformation modes was considered to be negligible. Increasing the weight also raises the concern that bending stress caused by gravity may affect the test results; even so but the generated bending stress was at most 0.5 MPa. Static strength of the test material covered in this report is 400 MPa or more, which can be neglected as sufficiently small even when the expected fatigue strength is considered. Actual measured relative strain obtained by the strain gauge when the specimen was excited in the resonance state is shown in Figure 4. The values predicted by the analysis agree well with the measured values.

![Figure 2. Photograph of experimental setup with specimen [6]](image-url)
Figure 3. Geometry (A) and strain contours (B) of the specimen [6]

Figure 4. Bending-strain distribution in specimen along the longitudinal axis [6]
2.4. Regulation of stress amplitude

Since the high-speed fatigue test proposed in this report does not include a load-measuring device such as a load cell, it is difficult to directly measure and control the bending stress applied to the specimen. In addition, since the stiffness of the specimen changes from moment to moment (due to fatigue damage and temperature change) and the strain gauge reaches its fatigue life earlier than the target material does, a method based on strain measurement by strain gauge is difficult to adopt. However, in general, fatigue diagrams obtained under conditions of constant stress amplitude are often used in reliability design assuming a mechanical structure exposed to high-cycle fatigue loading. Therefore, it is important to keep a constant load amplitude during the fatigue test. In the present study, a method for defining the bending stress by combining strain measurement by strain gauge and the above-described displacement measurement at a response point (free end) based on response acceleration and vibration frequency was used.

The conditions under which the fatigue test was conducted with constant stress amplitude are described below. As shown in Equation (1), the natural frequency of the specimen is proportional to the square root of its elastic modulus. This condition also applies to the specimen geometry continuously changing cross-sectional shape. Therefore, Equation (1) can be transformed to

\[ f^2 = C_1 E \]  

where \( C_1 \) is a proportionality constant depending on the shape of the specimen and \( E \) is the bending stiffness of the specimen. The response acceleration on the free end in resonance state is then taken as \( a \). Accordingly, displacement \( d \) in the deflection direction at the response-acceleration measurement position can be expressed as

\[ d = \frac{a}{(2\pi f)^2} \]  

As fatigue damage progresses, the deformation mode may change due to the occurrence of cracks or the like. However, within a range where at least the deformation mode can be regarded as constant, the relationship between displacement \( d \) and strain \( \varepsilon \) at the evaluation point of the specimen can be assumed to be proportional and given as

\[ \varepsilon = C_2 d \]  

Stress \( \sigma \) at the evaluation point is the calculated from Equations (2) to (4) as

\[ \sigma = \varepsilon E = C_2 \frac{a}{(2\pi f)^2} \frac{f^2}{C_1} = C_3 a \]  

where \( C_3 \) is a proportionality constant expressed as

\[ C_3 = \frac{C_2}{(4\pi^2 C_1)} \]  

Based on Equation (5), the stress can be uniquely determined only by the response acceleration measured by the acceleration sensor independent of the stiffness of the specimen as far as no significant damage occurs. That is, even if the stiffness changes during the test, if it is possible to obtain \( C_3 \) beforehand and measure the response-acceleration amplitude during the test, the stress amplitude applied to the specimen can be determined from Equation (5). As shown in Figure 5, a vibration test was preliminarily performed at low excitation acceleration (10 m/s^2) to obtain a \( C_3 \). \( C_3 \) can be calculated from measurement data of the strain and the response-acceleration and Equation (4) and (5). After that, the procedure was
shifted to the main fatigue test. The fatigue test was carried out by controlling the amplitude of excitation acceleration as a constant value. Stress amplitude was evaluated from the measured response-acceleration amplitude after completion of the test.

2.5. Consideration of rise in specimen temperature.
If repeated strain is applied to a resin material at high speed, as shown in Figure 5, the specimen heats up remarkably due to viscous loss. Under the assumption of a high-speed fatigue test, this heat generation may raise the test temperature and affect the results of the fatigue test. Therefore, to determine appropriate test conditions for maintaining the specimen temperature in the normal temperature range, one-dimensional thermal conduction in the cross-section direction of the test piece was considered, and temperature distribution in the test piece was estimated. In the first case considered, the specimen resin (a viscoelastic body) was subjected to periodic repeated strain. Energy loss per unit time is expressed as

\[ Q = f E'' \varepsilon^2 \pi \quad (7) \]

where \( f \) is repetition frequency, \( E'' \) is loss elastic modulus of the material, and \( \varepsilon \) is strain amplitude [5]. As expressed by Equation (7), heat generation is proportional to repetition frequency and the square of strain amplitude. In the next case considered, strain distribution in the cross-section direction of the specimen is considered. In bending mode, axial strain increases linearly from the neutral axis toward the specimen surface, so strain distribution in the cross-section direction is expressed as

\[ \varepsilon(x) = \frac{2}{t} \varepsilon_0 x \quad (8) \]

where \( x \) is distance from the neutral axis, \( \varepsilon(x) \) is strain at position \( x \), \( \varepsilon_0 \) is bending strain on the specimen surface, and \( t \) is thickness of the specimen. From Equations (7) and (8), heat distribution \( Q(x) \) in the cross-sectional direction can be expressed as

\[ Q(x) = \frac{4f E'' \pi \varepsilon_0^2}{t^2} x^2 \quad (9) \]
Next, under the assumption of one-dimensional steady-state heat conduction in the cross-sectional direction, the heat conduction equation can be written as

\[
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + Q(x) = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{4fE''\pi\varepsilon_0^2}{t^2} x^2 = 0
\]

(10)

where \( k \) is thermal conductivity of the specimen, and \( T \) is specimen temperature. In consideration of heat flux \( q(x) \) at position \( x \), the boundary condition can be expressed as follows. Since the heat flux is zero at the neutral-axis position, it follows that

\[
q(x = 0) = k \left. \frac{\partial T}{\partial x} \right|_{x=0} = 0
\]

(11)

And since heat transfer to the surrounding atmosphere occurs on the surface of the test piece, it follows that

\[
q \left( x = \frac{1}{2} t \right) = k \left. \frac{\partial T}{\partial x} \right|_{x=\frac{t}{2}} = h \left( T_b - T_{1_b} \right)
\]

(12)

where \( h \) is the heat-transfer coefficient, and \( T_{1_b} \) and \( T_b \) are surface temperature and environmental temperature, respectively. Solving the heat-conduction equation (Equation (10)) using the boundary conditions given by Equations (11) and (12), the temperature distribution in the cross-sectional direction is given as

\[
T = -\frac{fE''\pi\varepsilon_0^2}{3t^2} \left\{ \frac{x^4}{k} - \frac{t^3}{2k} - \frac{t^4}{16k} \right\} + T_b
\]

(13)

Cross-sectional temperature distribution in the specimen given by Equation (13) is shown in Figure 6. Loss elastic modulus was calculated as 126 MPa from the measured acceleration frequency response, which was separately performed, and the heat-transfer coefficient was estimated as 44 W/m²K from surface temperature measured during excitation. Thickness of the specimen was examined both in terms of the real value (3 mm) and twice of that value (6 mm). In addition, temperature distribution in the cross-sectional direction (similarly obtained by assuming uniaxial tensile-compression mode) is also shown in the figure. For all results, test frequency of 200 Hz and stress amplitude of 100 MPa were assumed as test conditions.

In the case of test piece thickness \( t = 3 \) mm in bending mode, the temperature rise is less than 20°C, and temperature distribution is almost uniform. Therefore, if stress amplitude is within the range of about 100 MPa, it is considered that the test can be carried out by keeping ambient temperature at about 0°C in order to maintain the temperature of the evaluation point in the room-temperature range. In the test, surface temperature of the specimen is measured with a thermocouple attached to the surface of the test piece. Based on the analysis result, the measured temperature can be considered the specimen temperature. In the experimental system used in the present study, although it is impossible to directly control specimen temperature during the fatigue test, environmental temperature was set to either 0°C or 30°C (i.e., no cooling). On the other hand, the uniaxial tensile-compression mode induced temperature rise of more than 50°C. If the test is carried out under a lower-temperature environment, it is possible to keep the test-piece temperature in the normal temperature range even in this testing mode. However, practical problems in regard to cooling (such as frost formation) remain. If the temperature distribution
of the specimen is focused on, it becomes clear that there is no noticeable difference in the slopes of the lines for bending mode and tensile-compression mode when specimen thickness was \( t = 3 \) mm. However, when thickness was \( t = 6 \) mm, not only absolute temperature rise exceeds 120°C but also the temperature distribution narrows by about 15°C. On the other hand, the temperature distribution in the bending mode is in the range of about 2°C. This result is due to the fact that the calorific value is smaller for a deeper position in the specimen (which is difficult to cool). Although the case of increased thickness was described here, the same tendency would be seen if a material having a smaller thermal conductivity were targeted, since thermal resistance between the neutral axis and the surface of the test piece would be increased. Therefore, the bending system adopted in the present study is considered to be able to cover a wider range of materials and specimen dimensions from the viewpoint of suppression of temperature rise and distribution.

![Cross-sectional distribution of temperature increase in specimens with thickness of 3 and 6 mm estimated under the assumption of one-dimensional heat transfer [6].](image)

**Figure 6.** Cross-sectional distribution of temperature increase in specimens with thickness of 3 and 6 mm estimated under the assumption of one-dimensional heat transfer [6].

Testing conditions: frequency: 200 Hz; stress amplitude: 100 MPa.

### 2.6. Low-frequency alternating bending-fatigue test

In order to test the accuracy of the tests results obtained at high frequencies, it is necessary to evaluate the influence of the test frequency on the test result. Accordingly, a test at lower frequency with the same test specimen under the same strain-distribution condition as the high-speed fatigue test was carried out, and the results were compared with the results from the high-speed test. A general fatigue-testing machine was used for a fatigue test for that comparative study (hereinafter referred to as “low-speed fatigue test”). Bending deformation is obtained from the resonance of the specimen in the high-speed fatigue test. For that reason, it is possible to adjust the natural frequency by adjusting the weight mounted on the free end of the specimen. However, in consideration of a spring-mass system, since the natural frequency is inversely proportional to the square root of the mass, it is practically difficult to test the test frequency at several hertz when the same specimen is used. Accordingly, a low-frequency fatigue test (low-speed fatigue test) with the same specimen, complete strain distribution and same stress ratio was performed using a hydraulic-actuator fatigue-testing machine (Model 8871, Instron).

A photograph of the experimental setup is shown in Figure 7. To make the strain distribution in the specimen the same as that in the resonated specimen, bending deformation was applied by a load applied at the point of weight attachment. In the high-speed fatigue test, to attain bending test in resonance state, the stress ratio has to be \( R = -1 \) as alternate loading. To achieve the same stress ratio in the low-speed fatigue test, the specimen was sandwiched from above and below with a two-way indenter (having a wedge shape) connected to the hydraulic actuator. In addition, when the specimen was mounted, so that
a bending moment is not generated at the loading point, a gap (about 0.3 mm) was set between the test piece and the tips of the indenters.

Figure 7. Photograph of experimental setup for low-speed fatigue testing [6].

Strain distributions based on the results of the static-load analysis and frequency-response analysis by the finite-element method under the assumptions that the low-speed fatigue test (with concentrated load applied) and the fast fatigue test (at about 230 Hz) were performed are compared in Figure 8. Both sets of results agree well; that is, the generated strain distributions are almost the same even though the way of exerting bending deformation was different.

The time histories of strain and load during the low-speed fatigue test are shown in Figure 9. The fatigue-testing machine was in the load-control mode, and load amplitude was 75 N with alternate loading (1 Hz). A sinusoidal waveform of the strain was observed, and it was confirmed that a fatigue test with stress ratio $R = -1$ is feasible. All tests were carried out in a normal temperature environment (25 to 30°C), and test frequency was 1 Hz. To record the change in stiffness of the specimen, the stroke of the actuator was recorded as a time series.

Figure 8. Strain distribution along longitudinal axis in the low-speed and high-speed tests [6].

Figure 9. Waveforms of load and strain in the low-speed test [6].
3. Results and discussions

3.1. Evaluation of fatigue damaging based on stiffness change

An example of the change in stiffness retention ratio during the test is shown in Figure 10. In the case of the high-speed fatigue test, the stiffness of the specimen was obtained from the change of its natural frequency. Since the residual stiffness measured by the acceleration sensor was evaluated in the frequency domain, it is less susceptible to the influence of drift and noise, and relatively stable measurements were obtained as compared to directly measured strain by strain gauge or extensometer. In the case of the low-speed fatigue test, stiffness retention ratio was obtained from the stroke change of the testing machine. Stroke change is influenced not only by change in the stiffness of the specimen but also by the contact state change between the indenters and the specimen, deformation of the indenters or the testing machine, and so on. Therefore, the measurements from the low-speed test included a large noise component compared with the measurements from the high-speed test.

Both of the low-speed fatigue test and the high-speed fatigue test showed a tendency of rapid decrease of stiffness after the stiffness retention ratio fell below 95%. In the low-speed fatigue test, the specimen was broken immediately after this rapid decrease. In the high-speed fatigue test, the response-acceleration waveform distorted from the sinusoidal waveform when the damage progresses and a crack develops. Therefore, the resonance tracking could not work before the specimen reaches final failure; in other words, the stress amplitude sometimes decreases remarkably as described above. Therefore, in consideration of the above result, the moment that the stiffness retention ratio reached 95% was considered to be the life of the specimen. In the case of the high-speed fatigue test, the stiffness reduction due to the temperature rise was corrected by referring to the relationship between stiffness and temperature of the test specimen acquired in advance. In addition, stress amplitude could not be controlled directly. Therefore, if the damping ratio of the specimen changes during the test, the stress amplitude fluctuates. Indeed, at the end of the specimen’s fatigue life, a decrease in stress amplitude, which is thought to be due to an increase in the specimen’s damping characteristic (due to an increase in internal friction [8]), was confirmed. Therefore, as the value of the stress amplitude, an average value from the time immediately after the start of resonance until the stiffness retention ratio reached 95% was used. In addition, it was judged that the test results with fluctuation width exceeding 10% of the average value could not be regarded as a constant stress amplitude and excluded from the evaluation results.

Figure 10. Residual stiffness of specimens during fatigue test. [6]
3.2. Observation of damaged specimen

Examples of the specimens subjected to the high-speed fatigue test and the low-speed fatigue test are shown in Figures 11(a) and (b), respectively. Visible cracks are observed in the test piece subjected to the high-speed fatigue test. The positions where the cracks occurred are within the range of approximately ±2 mm from the maximum stress position. It was judged that the error of the stress amplitude within this range was within -3% of the maximum value, so its influence on the test result was small. In addition, when the crack was observed in detail, there was a case where it was slightly discoloured to brown. It was considered to be a discoloration due to frictional heat generated by sliding fracture surfaces in the cracks. In fact, in some cases, a sharp rise in the specimen temperature was observed after the stiffness retention ratio fell below 95%. In addition, in the vicinity of the crack position, a spot-like whitening (which is thought to be caused by separation of the matrix resin and the glass cloth) was observed. In the low-speed-fatigue-test specimen [Figure 11(b)], whitening was also observed around the fracture surface of the specimen. However, the influence of the frequency on damaging-process is not sufficiently studied at present because in the case of high-speed fatigue test, it is impossible to continue the test until final failure (as described above), and heat generation due to sliding between fracture surfaces of cracks may affect the failure mode.

![Figure 11](image_url)

**Figure 11.** Photographs of specimens of glass fibre-epoxy laminate after fatigue tests: (a) high-speed test and (b) low-speed test [6].

3.3. S-N curve

Based on the fatigue-life criteria described in Section 3.1 (stiffness retention ratio of 95%), S-N curves for both tests were derived. S-N curves derived from the results of the low-speed test at room temperature (ambient: 20-25°C), high-speed test at room temperature (specimen: 8-15°C; ambient: 0°C), and high-temperature conditions (specimen: 40-60°C; ambient: 30°C) are shown in Figure 12. It is clear that fatigue strength decreases by about 10% to 20% under the high-temperature condition compared to the room-temperature condition in regard to the high-speed test. It can be speculated that fatigue strength of this material varied under the influence of temperature. This result agrees with the previous report that if test frequency is raised, the specimen lifetime will decrease due to temperature rise (Rotem, 1993). The results from the low-speed test and the high-speed test obtained under room temperature conditions are focused on hereafter. For glass-fibre-reinforced resin and carbon-fibre-reinforced resin, it is known that a high cycle fatigue curve obtained under the load-control condition follows the power law described as
\[ S = C N^{\frac{1}{m}} \] 

where \( S \) is stress amplitude, \( N \) is number of repeating cycles, and \( m \) and \( C \) are constants [8]. For fibre-reinforced resins using epoxy resin as a matrix, it has been reported that \( m \) (which represents the slope of the S-N curve) is within the range of about 6 to 15 [9]. Approximated curves obtained from Eq. (14) are shown for the low-speed test and the high-speed test in Figure 12. A high-cycle fatigue range (\( 10^4 \) times or more) was chosen for the approximation range. Both of sets of results agree well, and it is considered that the high-speed test provides comparable results to the test at several hertz if cooling was carried out properly to suppress excessive temperature rise. However, comparable fatigue lives were not obtained in the high-speed test and the low-speed test due to difficulties such as test time (for the low-speed test) at low stress levels and frosting (for the high-speed test) at high stress levels. In the future, the author plans to expand the stress-amplitude range of each test and verify the equivalence of both tests. In the present study, evaluation was limited only to a single material/laminated structure. In the future, we plan to conduct tests on different resin materials or composite materials with different laminated constructions and confirm the applicable range of the devised test method.

![Figure 12. S-N plot of glass fibre-epoxy laminate obtained from high-speed and low-speed fatigue tests. (Stress ratio: \( R = -1 \)](image)

4. Conclusions

A high-speed fatigue test method utilizing resonance applicable to resins including fibre-reinforced materials was devised and to a general-purpose glass-epoxy laminate to evaluate its effectiveness. The results of the evaluation are summarized below

- When the fatigue test was conducted at a test frequency of about 230 Hz, it was found that the results plotted on the S-N curve were approximately the same as the test results performed at test frequency of 1 Hz if the specimen temperature was appropriately controlled.
- Specimen temperature during the fatigue test was estimated by assuming one-dimensional thermal conduction. It was found that the specimen temperature can be kept sufficiently in the normal temperature region by external cooling within the assumed stress amplitude range even if the test is performed at loading frequency of more than 200 Hz.
These results indicate that the devised test method has is suitable for obtaining fatigue strength of resins in a short period of time.

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