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The Effect of Temperature on Fatigue Strength and Cumulative Fatigue Damage of FRP Composites

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Abstract

Polymer-matrix composites are viscoelastic materials and their mechanical properties are significantly influenced by temperature. The present study intends to investigate the effect of temperature on cumulative fatigue damage ($D$) of laminated fibre-reinforced polymer (FRP) composites. The fatigue strength ($S$-$N$ relation) of FRP composite laminates was formulated with temperature-dependent parameters. The effect of temperature was further included in the fatigue damage approach formulated earlier by Varvani and Shirazi. The analysis was developed to assess the fatigue damage of FRP composites at various temperatures ($T$). Inputs of the proposed analysis included temperature-dependent parameters including Young’s modulus ($E$), ultimate tensile strength ($\sigma_{ult}$), and fatigue life ($N_f$). The proposed temperature-dependent terms and equations were evaluated with the experimental data available in the literature. Temperature dependant-parameters of Young’s modulus, ultimate tensile strength, and $S$-$N$ relation were found to be responsive when used for unidirectional, cross-ply, and quasi-isotropic FRP laminates. The proposed fatigue damage model was examined using six sets of fatigue damage data and was found promising to predict the fatigue damage of unidirectional (UD) and orthogonal woven FRP composites at different temperatures.

Keywords: Temperature; Young’s Modulus; Ultimate Tensile Strength; $S$-$N$ Relation; Fatigue Damage; FRP Composites.

1. Introduction

The major fatigue models and life time methodologies for FRP composites are classified in three categories: (i) fatigue life models, which do not take into account the actual degradation mechanisms, such as matrix cracks and fibre fracture, but use $S$-$N$ curves or Goodman-type diagrams and introduce some fatigue failure criteria [1-4], (ii) phenomenological models for residual stiffness/strength [1,5-8], and (iii) progressive damage models which analyze the fatigue damage based on some measurable damage variables such as transverse matrix cracks and delamination size [1,9-11].

The fatigue damage model employed in this study is constructed based on stiffness degradation of materials over life cycles. Stiffness degradation damage models [5-7] are reliable approaches relating damage progress of FRP...
composite material properties, including the properties of the matrix, fibre, and fibre-matrix interface as the number of stress cycles progresses. Ramkrishnan–Jayaraman and Varvani-Farahani–Shirazi damage models [5,6] were used as the backbone of analysis in this paper. Mechanical properties of FRP composite laminates including their microconstituents are further formulated as a function of operating temperatures. Temperature-dependent parameters of Young's modulus and ultimate tensile strength as inputs of the damage model characterize the damage of FRP composite specimens at various operating temperatures.

2. Temperature-Dependant Parameters in Damage Assessment

The progressive development of damage during fatigue life can be overviewed with the aid of Figure 1, which represents the development of damage during the fatigue life of unidirectional composite materials [6].

![Figure 1: Three regions of cracking mechanism in unidirectional composites [6].](image)

In region I, multiple crack initiations within the matrix are grouped together during the first 20% of the fatigue life. Region II commences as matrix cracks reach the vicinity of fibre. As the number of cycles increases, the crack grows along the fibre-matrix interface. This region is characterized with a larger life span and a lower slope of damage progress. In region III, with a shorter life span, fibre breakage occurs shortly after damage has been accumulated during regions I and II [6].

The previously-developed stiffness-based damage relations [5,6] have modeled the fatigue damage \( D \) of unidirectional FRP composites as a function of the maximum applied stress \( \sigma_{\text{max}} \), number of loading cycles \( N \), load or stress ratio \( R \), and material and structural properties, such as Young’s modulus \( E \), volume fraction \( V \), and the angle between the fibre and loading direction \( \theta \). In this study, the effect of operating temperature \( T \) on the fatigue damage \( D \) is proposed as:

\[
D = \left\{ \left( 1 - \frac{F}{E_e(T)} \right) \left( 1 - f^* \right) \ln\left( \frac{N + 1}{nN_f} \right) + \left( 1 - \frac{F}{E_e(T)} \right) f^* \left( \frac{N}{nN_f} \right) \right\} + \left\{ \frac{F}{E_e(T)} \left( 1 - \frac{\sigma_{\text{max}} (1 - R)}{2\sigma_{\text{ult}}(T)} \right) \ln\left( \frac{1 - N}{nN_f} \right) \right\} 
\]

where \( N_f \) = fatigue life or number of cycles to failure,
\( n \) = the assumed percentage of run-out or drop in stiffness,
\( E_e(T) \) = Young’s modulus of composite at temperature \( T \),
\( f^* \) = fibre/matrix interface strength parameter, \( 0 \leq f^* \leq 1 \),
\( R = \text{stress ratio } (\sigma_{\text{min}}/\sigma_{\text{max}}) \),
\( \sigma_{\text{max}} \) = maximum applied fatigue stress, and
\( \sigma_{\text{ult}}(T) \) = ultimate tensile stress at temperature \( T \).

Term \( F \) in Equation (1) varies based on composite laminate lay-up. For unidirectional composites, term \( F \) extracted from the rule of mixtures becomes \( E_f V_f \cos(\theta) \). For orthogonal woven composites, the rule of mixtures
results in \( F = V_f^*E_f \). Note that \( V_f^* = K_fV_f \) corresponds to the volume fraction of fibres which are aligned in the loading direction. \( E_f \) represents Young’s modulus of fibre.

Similar to the previously-developed fatigue damage formulations, Equation (1) holds terms of damage in three regions of the matrix, matrix-fibre interface, and fibre. Using Equation (1), the procedure of damage analysis includes:

i. Define input parameters of \( E_f, V_f^*, E(T), f^*, \sigma_{ad}(T), \sigma_{max}, R, n, \) and \( N_f \).

ii. Calculate the values of damage cycle-by-cycle.

iii. Calculate the total damage over fatigue life cycles.

To implement the effect of temperature in Equation (1), the temperature-dependant parameters of \( \sigma_{ad}(T) \) and \( E(T) \) or \( E_c(T) \) are required to be formulated as:

\[
\sigma_{ad}(T) = \sigma_{ad}(T_0) \left[ 1 - \frac{\left( \frac{\sigma_{ad}(0)}{\sigma_{ad}(T_0)} - 1 \right)}{\ln \left( \frac{T_0}{T_m} \right)} \ln \left( \frac{1 - T}{T_m} \right) \right]
\]

(2)

\[
E(T) = E(T_0) \left[ 1 - \frac{\left( \frac{E(0)}{E(T_0)} - 1 \right)}{\ln \left( \frac{T_0}{T_m} \right)} \ln \left( \frac{1 - T}{T_m} \right) \right]
\]

(3)

In the above two equations, \( \sigma_{ad}(T) \) and \( E(T) \) are, respectively, the ultimate tensile strength and the Young’s modulus at an arbitrary temperature \( T \); \( \sigma_{ad}(T_0) \) and \( E(T_0) \) are the values of the physical parameters at the reference temperature \( T_0 \) (\( T_0 \) is normally assumed as room temperature); \( T_m \) denotes the polymer melting temperature of the composites. \( T, T_0, \) and \( T_m \) are all in Kelvin.

Constant \( C \) in Equations (2) and (3) corresponds to the sensitivity of material or mechanical property to temperature variation and is defined based on the mechanical property. In Equations (2) and (3), \( C \) has been defined based on the ultimate tensile strength and Young’s modulus, respectively. In these equations, \( \sigma_{ad}(0) \) and \( E(0) \) are the ultimate tensile strength and Young’s modulus at absolute zero temperature (\( 0 \text{ K} = -273^\circ \text{C} \)), respectively.

In Equation 1, fatigue life data \( N_f \) obtained at temperature \( T \) is used as an input of the damage equation. However, to get more familiar with the effect of temperature on \( N_f \), the fatigue strength (S-N relation) of FRP composite laminates is also formulated to have the temperature-dependent parameters.

\[
\sigma_{max} = A(T_0) \left[ 1 - \frac{A(0)}{A(T_0)} \right] \ln \left( \frac{1 - \frac{T_0}{T_m}}{\ln \left( \frac{1 - \frac{T_0}{T_m}}{\ln \left( \frac{T_0}{T_m} \right)} \right)} \right] (N_f(T))
\]

(4)

Equation (4) is the proposed temperature-dependent power-law S-N relation. It is known that by plotting \( \sigma_{max} \) versus the logarithm of \( N_f(T) \), a curve very similar to a line is obtained in which coefficient \( A(T) \) is the \( y \)-intercept at \( N = 1 \) cycle, and exponent \( m(T) \), which has a negative value, represents the slope of the curve. As defined earlier, \( T, T_0, \) and \( T_m \) are all in Kelvin.
3. Evaluation of the Temperature-Dependent Parameters

3.1. Evaluation of Temperature-Dependent Monotonic Relations

Experimental data extracted from the literature [12-15] have been used to evaluate the formulations proposed for the ultimate tensile strength and Young’s modulus. In the following, two extensive sources of experimental data used in this paper are introduced.

Jen et al. [15] tensile tested samples made of graphite/PEEK (AS-4/PEEK) prepregs with different lay-ups of cross-ply [0/90]_{4S} and quasi-isotropic [0/+45/90/-45]_{2S} laminates. After curing, the laminates were cooled down at room temperature (RT) and taken out from the hot press. A cutting machine with diamond blade and water cooling was used to cut the laminates into \( L = 240 \text{ mm} \), \( W = 25.4 \text{ mm} \), and \( t = 2 \text{ mm} \) coupons, according to ASTM D3039-93. Copper plate was considered as end tabs by NP-50 two-component adhesive. The fibre volume fraction of the specimens was reported to be about 61%. The tension tests on the specimens were performed at RT (25°C), 50°C, 75°C, 100°C, 125°C, 150°C, and 175°C.

Shen and Springer [12,13] have measured ultimate tensile strength and buckling modulus of a special kind of graphite/epoxy specimens called Thornal 300/Fiberite 1034 at different temperatures. The size of the specimens in the tension test was reported as \( L = 101 \text{ mm} \), \( W = 12.7 \text{ mm} \), and \( t = 0.9 \text{ mm} \), and the size in the buckling tests was reported as \( L = 36-318 \text{ mm} \), \( W = 4.76 \text{ mm} \), and \( t = 0.9 \text{ mm} \). Shen and Springer have also evaluated the ultimate tensile strength and Young’s modulus variations with temperature using different sets of data available in the literature. The summary of the test data is discussed as follows: Thornel 300/Narmco 5208 was tensile tested at a temperature range between 300-450 K, reported by Hofer et al. [16] and Husman [17]. Hertz [18] performed monotonic tests on HT-S/(8183/137-NDA-BF3:MEA) at various temperatures of 200-450 K. The experimental measurements of Browning et al. [19] on the influence of temperature on \( \sigma_{ult} \) for Herculus AS-5/3501 were ranged from 300 K to 425 K. Further experiments were conducted to obtain the effect of temperature on \( \sigma_{ult} \) for boron/Narmco 5505 by Kaminski [20]. In addition to \( \sigma_{ult} \) experiments, Hofer et al. [16] conducted a new sets of tensile tests to evaluate \( E \) with temperature change between 300 K to 450 K.

The calculated mechanical properties at various operating temperatures were compared with the experimental values in Figures 2(a)–(c). These figures show good correlations between the experimental data and the predicted values. The ultimate tensile strength shows a steeper decay than Young’s modulus as operating temperature increases. These figures verify that the Young’s modulus of on-axis composites is less sensitive to temperature change. For composites with the lay-up of 90°, the degradation of the Young’s modulus becomes more pronounced as the temperature increases.

3.2. Evaluation of the Fatigue S-N Relation

Experimental data extracted from the literature [15,21] have been used to evaluate fatigue S-N relation (4). The following presents the two sources of experimental data used in this study:

Jen et al. [15] conducted tension-tension fatigue tests using MTS 810 testing machine in load control condition with a stress ratio of \( R = 0.1 \) and sinusoidal waveform at a frequency of 5 Hz on graphite/PEEK prepregs. The prepregs were used to make AS-4/PEEK cross-ply [0/90]_{4S} and quasi-isotropic [0/+45/90/-45]_{2S} laminate samples. The specimen size and fibre volume fraction were given as \( L = 240 \text{ mm} \), \( W = 25.4 \text{ mm} \), and \( t = 2 \text{ mm} \) and \( V_f=61\% \). The glass transition temperature \( (T_g) \) of PEEK was reported to be 416 K. The fatigue tests were performed at RT (25°C), 75°C, 100°C, 125°C, and 150°C. The specimens were fatigue tested for up to 10^6 cycles.
Figure 2: Ultimate tensile strength and Young’s modulus of (a) different 0° FRP composites, (b) [0/90]_4S and [0/+45/90/-45]_2S AS-4/PEEK. Ultimate tensile strength and Young’s modulus of (c) different 90° FRP composites as a function of temperature. Experimental data have been extracted from Refs. 12-15.
Kawai and Taniguchi [21] fatigue tested composite laminate samples of carbon/epoxy with woven fabric lay-ups. The prepreg tape F6343B-05 (TORAY) made of carbon fibre T300 and thermosetting epoxy resin # 2500 ($T_g = 403$ K). Five kinds of plain coupon specimens with different fibre orientations ($\theta = 0, 15, 30, 45, \text{ and } 90^\circ$) were cut from 400 mm by 400 mm laminate panels. The off-axis angle $\theta$ has been defined as the angle between the loading direction and the warp direction of the specimens. The dimensions of the specimens were reported as $L = 200$ mm, $W = 20$ mm, and $t = 3$ mm. Tension–tension fatigue tests were performed on the specimens at room temperature (25°C) and the temperature of 100°C under load control condition. The fatigue load was applied in a sinusoidal waveform with a frequency of 10 Hz and stress ratio $R = 0.1$. The samples were fatigue tested for up to $10^6$ cycles.

To evaluate Equation (4), temperature-dependent exponent $m$ and coefficient $A$ were first calculated (see Figures 3(a) and 3(b)). Equation (4) has been used to assess fatigue life for cross-ply and quasi-isotropic graphite/epoxy laminates and various woven graphite/epoxy composites with off-axis angles of $15^\circ$, $30^\circ$, and $45^\circ$; Figures 3(c)–(f) present the predictions.

3.3. Evaluation of the Fatigue Damage Model

Hiwa et al. [22] tested composite samples of plain-woven glass cloth (WF 350) and glass mat (MC 300S) as the reinforced fibres embedded within the matrix of polyvinyl ester resin. The FRP composite samples made by the materials have been laminated by the hand lay-up method. The number of plies in the polyvinyl ester/glass cloth and polyvinyl ester/glass mat were 5 and 3, respectively. Also, the volume fraction of the glass fibres in the cloth and mat were 48% and 35%, respectively. To measure the fatigue damage of the composites versus number of cycles at various temperatures, different fatigue tests with the loading frequency of 16.7 Hz and the stress ratio of 0 were performed on the specimens. The composites with glass cloth fibres were tested with the maximum stress of 130 MPa at RT (25°C), 50°C, and 70°C. However, the glass mat-reinforced polyvinyl ester composites were tested with the maximum stress of 90 MPa at RT (25°C), 100°C, and 150°C. In this paper, to evaluate the proposed fatigue damage model, six sets of $D$-$N$ data have been extracted from the described fatigue damage experiments. Figures 4(a)–(f) present the evaluation of fatigue damage over life cycles at various temperatures. These figures show the fact that the experimental data and predicted damage values using the proposed damage model are in good agreement.
Figure 3: (a) \(A-T\) and (b) \(m-T\) relations in Equation (4) evaluated with the experimentally obtained intercepts and slopes for \([0/90]_4S\) and \([0/+45/90/-45]_2S\) AS-4/PEEK, and different woven graphite/epoxy composites. \(S-N\) curves of (c) \([0/90]_4S\) and (d) \([0/+45/90/-45]_2S\) AS-4/PEEK and \(S-N\) curves of plain-woven (e) \((15^\circ)\), (f) \((30^\circ)\) for T300/Epoxy#2500 composites at different temperatures modeled by Equation (4). Experimental data have been extracted from Ref. 15 for the AS-4/PEEK and from Ref. 21 for the T300/Epoxy#2500 composite samples.
Figure 4: Fatigue damage of (a–c) glass cloth/polyvinyl ester and (d–f) glass mat/polyvinyl ester versus number of cycles at different temperatures. Experimental data have been extracted from Ref. 22.
4. Discussion of Results

As illustrated in Figures 2(a)–(d), the curves generated using the proposed $\sigma_{ult} - T$ and $E - T$ relations showed good correlations with experimental data. Based on the calculated results presented in the figures, the effect of temperature on 0° plies is less than $[0/90]_{4S}$, $[0/+45/90/-45]_{2S}$, and 90°, while 90° lay-ups have the highest sensitivity to temperature changes. The sensitivity to temperature is also different between the ultimate tensile strength and Young’s modulus of a composite material. These figures illustrate the fact that the effect of temperature on the ultimate tensile strength is more pronounced than that on Young’s modulus. In the proposed temperature-dependent formulation, the sensitivity of the mechanical properties to temperature is evaluated based on the constant $C$. The bigger $C$ corresponds to a higher temperature sensitivity.

The effect of temperature on fatigue strength ($S-N$ relation) of FRP composite laminates was included as Equation (4). A comparison between the experimentally obtained fatigue lives and the predicted lives based on $S-N$ relation (4) is presented in Figure 5(a). This figure includes five different materials and lay-ups fatigue tested at various temperatures. The figure compares sixteen different sets of the experimental life data with the predicted fatigue lives. This figure, with over 130 fatigue life data tested at various temperatures, successfully collapses 80% of fatigue life data between the upper and the lower bands shown by dashed lines. The 20% of the data which deviated from the ±3 bands were attributed to temperatures near the glass transition temperature $T_g$, at which the matrix shows a change in status.

5. Conclusions

In this study, the cumulative fatigue damage model of Varvani-Farahani–Shirazi was further developed based on the temperature-dependent parameters of $\sigma_{ult}(T)$ and $E(T)$ to assess the fatigue damage of FRP composites at various temperatures. The proposed temperature-dependent fatigue damage model was also evaluated using six sets of damage data extracted from the literature. Comparison of the $D-N$ curve predicted using Equation (1) and the $D-N$ experimental values were found to be in good agreement. The main point concluded from the $D-N$ graphs is that, with increasing temperature, the cumulative fatigue damage is increased and vice versa. Figure 5(b) clearly illustrates the variation of fatigue damage with temperature.
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