

Fatigue Life Prediction of Carbon Fiber-Reinforced Ceramic-Matrix Composites at Room and Elevated Temperatures. Part II: Experimental Comparisons

Li Longbiao¹

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Abstract This paper follows on from the earlier study (Part I) which investigated the fatigue behavior of unidirectional, cross-ply and 2.5D C/SiC composites at room and elevated temperatures. In this paper, a micromechanics approach to predict the fatigue life $S-N$ curves of fiber-reinforced CMCs has been developed considering the fatigue damage mechanism of interface wear or interface oxidation. Upon first loading to fatigue peak stress, matrix multicroacking and fiber/matrix interface debonding occur. The two-parameter Weibull model is used to describe fibers strength distribution. The stress carried by broken and intact fibres on the matrix crack plane under fatigue loading is determined based on the Global Load Sharing (GLS) criterion. The fibres failure probabilities under fatigue loading considering the degradation of interface shear stress and fibres strength have been obtained. When the broken fibres fraction approaches critical value, the composite would fatigue fail. The fatigue life $S-N$ curves of unidirectional, cross-ply and 2.5D C/SiC composites at room and elevated temperatures have been predicted. The predicted results agreed with experimental data.

Keywords Ceramic-matrix composites (CMCs) · $S-N$ curve · Life prediction · Fatigue · Hysteresis loops · Matrix multicroacking · Interface debonding

1 Introduction

The author, in the previous study, presents an experimental analysis on the fatigue behavior in C/SiC ceramic-matrix composites (CMCs) with different fiber preforms, i.e., unidirectional, cross-ply and 2.5D woven, at room and elevated temperatures in air atmosphere. The experimental fatigue life $S-N$ curves of C/SiC composites corresponding to different stress

✉ Li Longbiao
llb451@nuaa.edu.cn

¹ College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, No. 29, Yudao St., Nanjing 210016, People's Republic of China

levels and test conditions have been obtained. The damage evolution processes under fatigue loading have been analyzed using fatigue hysteresis modulus and fatigue hysteresis loss energy. By comparing the experimental fatigue hysteresis loss energy with theoretical computational values, the interface shear stress corresponding to different peak stress, fiber preforms and test conditions have been estimated. It was found that the degradation of interface shear stress and fiber strength caused by oxidation markedly decreases the fatigue life of C/SiC composites at elevated temperature.

In this paper, a micromechanics approach to predict the fatigue life S–N curves of fiber-reinforced CMCs has been developed considering the fatigue damage mechanism of interface wear or interface oxidation. The applied stress carried by broken and intact fibres on the matrix crack plane under fatigue loading has been determined based on the Global Load Sharing (GLS) criterion. The broken fibres fraction under fatigue loading has been obtained by combining fibres failure model with interface shear stress and fibres strength degradation model. The fatigue life S–N curves of unidirectional, cross-ply and 2.5D C/SiC composites at room and elevated temperatures have been predicted.

2 Life Prediction Model

Upon first loading to fatigue peak stress, matrix multicracking and fiber/matrix interface debonding occur. There would be partially fibers failed in the interface debonded region or interface bonded region. Under fatigue loading at constant peak stress, fibers fail due to degradation of interface shear stress and fibers strength. When the broken fibers fraction approaches critical value, the composite would fatigue fail.

When fibers begin to break, the loads dropped by broken fibers would be transferred to intact fibers in the cross-section. Two dominant failure criteria are present in the literatures for modeling fibers failure, i.e., Global Load Sharing criterion (GLS) [1, 2] and Local Load Sharing criterion (LLS) [3–5]. The GLS criterion assumes that the load from any one fiber is transferred equally to all other intact fibers at the same cross-section plane. The GLS assumption neglects any local stress concentrations in the neighborhood of existing breaks, and is expected to be accurate when the interface shear stress is sufficiently low.

The two-parameter Weibull model is adopted to describe fiber strength distribution, and the GLS assumption is used to determine the load carried by intact and fracture fibers [2].

$$\frac{\sigma}{V_f} = T[1-P(T)] + \langle T_b \rangle P(T) \quad (1)$$

where $\langle T_b \rangle$ denotes the load carried by broken fibers; and $P(T)$ denotes the broken fibers fraction.

$$P(T) = 1 - \exp \left\{ - \left(\frac{T}{\sigma_c} \right)^{m_f + 1} \left(\frac{\sigma_o}{\sigma_o(N)} \right)^{m_f} \frac{\tau_i}{\tau_i(N)} \right\} \quad (2)$$

where m_f denotes the fiber Weibull modulus; and σ_c denotes the fiber characteristic strength of a length δ_c of fiber [2].

$$\sigma_c = \left(\frac{l_o \sigma_o^{m_f} \tau_i}{r_f} \right)^{1/m_f+1}, \delta_c = \left(\frac{\sigma_o r_f l_o^{1/m_f}}{\tau_i} \right)^{m_f/m_f+1} \tag{3}$$

where l_o denotes the reference length; and σ_o denotes the fiber reference strength of a length of l_o of fiber. $\sigma_o(N)$ denotes the fiber strength at the N th cycle. Lee and Stinchcomb [6] performed fiber fracture mirror experiments of CMCs under scanning electron microscope, and found that the fiber strength degrades with cycles increasing under cyclic loading.

$$\sigma_o(N) = \sigma_o [1 - p_1 (\log N)^{p_2}] \tag{4}$$

where p_1 and p_2 are empirical parameters. $\tau_i(N)$ denotes the interface shear stress at the N th cycle. Evans et al. [7] developed the interface shear stress degradation model.

$$\tau_i(N) = \tau_{i0} + [1 - \exp(-\omega N^\lambda)] (\tau_{i\text{min}} - \tau_{i0}) \tag{5}$$

where τ_{i0} denotes initial interface shear stress; $\tau_{i\text{min}}$ denotes steady-state interface shear stress; N is the cycle number; and ω and λ are empirical parameters.

When fibers fracture, the fiber stress would drop to zero at the break point, and the stress in the fiber builds up through interface shear stress.

$$T_b(x) = \frac{2\tau_i(N)}{r_f} x \tag{6}$$

The slip length l_f required to build the fiber stress up to its previous intact value is given by Eq. (7).

$$l_f = \frac{r_f T}{2\tau_i(N)} \tag{7}$$

The probability distribution $f(x)$ of the distance x of a fiber break from reference matrix crack plane, provided that a break occurs within a distance $\pm l_f$, is given by Eq. (8). [8]

$$f(x) = \frac{1}{P(T)l_f} \left(\frac{T}{\sigma_c} \right)^{m_f+1} \left(\frac{\sigma_o}{\sigma_o(N)} \right)^{m_f} \frac{\tau_i}{\tau_i(N)} \times \exp \left\{ - \left(\frac{x}{l_f} \right) \left(\frac{T}{\sigma_c} \right)^{m_f+1} \left(\frac{\sigma_o}{\sigma_o(N)} \right)^{m_f} \frac{\tau_i}{\tau_i(N)} \right\}, x \in [0, l_f] \tag{8}$$

Using Eqs. (6) ~ (8), the average stress carried by broken fibers is given by Eq. (9).

$$\begin{aligned} \langle T_b \rangle &= \int_0^{l_f} T_b(x) f(x) dx \\ &= \frac{T}{P(T)} \left(\frac{\sigma_c}{T} \right)^{m_f+1} \left(\frac{\sigma_o(N)}{\sigma_o} \right)^{m_f} \frac{\tau_i(N)}{\tau_i} \left\{ 1 - \exp \left[- \left(\frac{T}{\sigma_c} \right)^{m_f+1} \left(\frac{\sigma_o}{\sigma_o(N)} \right)^{m_f} \frac{\tau_i}{\tau_i(N)} \right] \right\} \\ &\quad - \frac{T}{P(T)} \exp \left\{ - \left(\frac{T}{\sigma_c} \right)^{m_f+1} \left(\frac{\sigma_o}{\sigma_o(N)} \right)^{m_f} \frac{\tau_i}{\tau_i(N)} \right\} \end{aligned} \tag{9}$$

Substituting Eq. (9) into Eq. (1), it leads to the form of

$$\frac{\sigma}{V_f} = T \left(\frac{\sigma_c}{T} \right)^{m_f+1} \left(\frac{\sigma_o(N)}{\sigma_o} \right)^{m_f} \frac{\tau_i(N)}{\tau_i} \left\{ 1 - \exp \left[- \left(\frac{T}{\sigma_c} \right)^{m_f+1} \left(\frac{\sigma_o}{\sigma_o(N)} \right)^{m_f} \frac{\tau_i}{\tau_i(N)} \right] \right\} \quad (10)$$

Using Eqs. (4), (5) and (10), the stress T carried by intact fibers at the matrix crack plane can be determined for different fatigue stresses. Substituting Eqs. (4), (5) and the intact fiber stress T into Eq. (2), the fiber failure probabilities corresponding to different number of applied cycles can be determined. When the broken fibers fraction approaches critical value, the composite would fatigue fail.

Under fatigue loading, the interface shear stress and fiber strength in the 0° plies or longitudinal yarns of cross-ply and 2.5D CMCs would decrease with the increase of applied cycles. When the broken fibers fraction in the 0° plies or longitudinal yarns approaches the critical value, the composite would be failure. In the cross-ply and 2.5D CMCs, the fiber volume fraction V_f in Eq. (10) should be the fiber volume fraction in the 0° plies or longitudinal yarns along loading direction.

3 Experimental Comparisons

The fiber/matrix interface shear stress of unidirectional, cross-ply and 2.5D woven C/SiC composites at room and elevated temperatures has been estimated by comparing experimental fatigue hysteresis loss energy with theoretical computational values [9]. Then the values of interface shear stress were used to determine the parameters of Evans–Zok–McMeeking model [7]. And the fatigue life S–N curves of unidirectional, cross-ply and 2.5D C/SiC composites at room and elevated temperatures can be predicted using the micromechanics approach by combining fibers failure model with interface shear stress degradation model [7] and fibers strength degradation model [6].

3.1 Unidirectional C/SiC Composite

3.1.1 Room Temperature

The interface shear stress of unidirectional C/SiC composite at room temperature has been estimated by comparing experimental fatigue hysteresis loss energy with theoretical computational values [9]. The interface shear stress versus applied cycles has been simulated by Evans–Zok–McMeeking model [7], as shown in Fig. 1a, in which the model parameters are given by $\tau_{i0}=8$ MPa, $\tau_{imin}=0.3$ MPa, $\omega=0.04$ and $\lambda=1.5$. The interface shear stress degrades from 8 MPa at the 1st cycle to 0.3 MPa at the 100th cycle. The fibers strength degradation curve is predicted by Lee–Stinchcomb model [6], in which the model parameters are given by $p_1=0.01$ and $p_2=1.0$.

The broken fibers fraction under fatigue peak stress of $\sigma_{max}=267$ and 260 MPa corresponding to different number of applied cycles curve is illustrated in Fig. 1b, in which the broken fibers fraction increases with the increase of fatigue peak stress. Under fatigue loading, the broken fibers fraction increases with the increase of applied cycles due to interface wear. Under fatigue peak stress of $\sigma_{max}=267$ MPa, the specimen fatigue failed after 31 cycles. Under fatigue peak stress of $\sigma_{max}=260$ MPa, the specimen fatigue failed after 400 cycles. The broken

fibers fraction versus applied cycles curve can be divided into two regions, i.e., (1) at the first 20 cycles, the broken fibers fraction increases rapidly due to degradation of interface shear stress and fibers strength; (2) when the interface shear stress approaches steady-state value, fibers failure is mainly controlled by fibers strength degradation, which makes the broken fibers fraction increase slowly, as shown in Fig. 1b. When the broken fibers fraction approaches critical value, the composite would fatigue fail.

The experimental and predicted fatigue life S–N curves of unidirectional C/SiC composite at room temperature are illustrated in Fig. 1c, in which the fatigue limit stress approaches 88 % of tensile strength. The predicted fatigue life S–N curve can be divided into two regions, i.e., (1) the A–B part is affected by the degradation of interface shear stress and fibers strength; and (2) when the interface shear stress approaches steady-state value, the B–C part is only affected by fibers strength degradation, as shown in Fig. 1c.

3.1.2 Elevated Temperature

The interface shear stress of unidirectional C/SiC composite at an elevated temperature of 800 °C in air atmosphere has been estimated by comparing experimental fatigue hysteresis loss energy with theoretical computational values [9]. The interface shear stress versus applied cycles has been simulated by Evans–Zok–McMeeking model [7], as shown in Fig. 2a, in

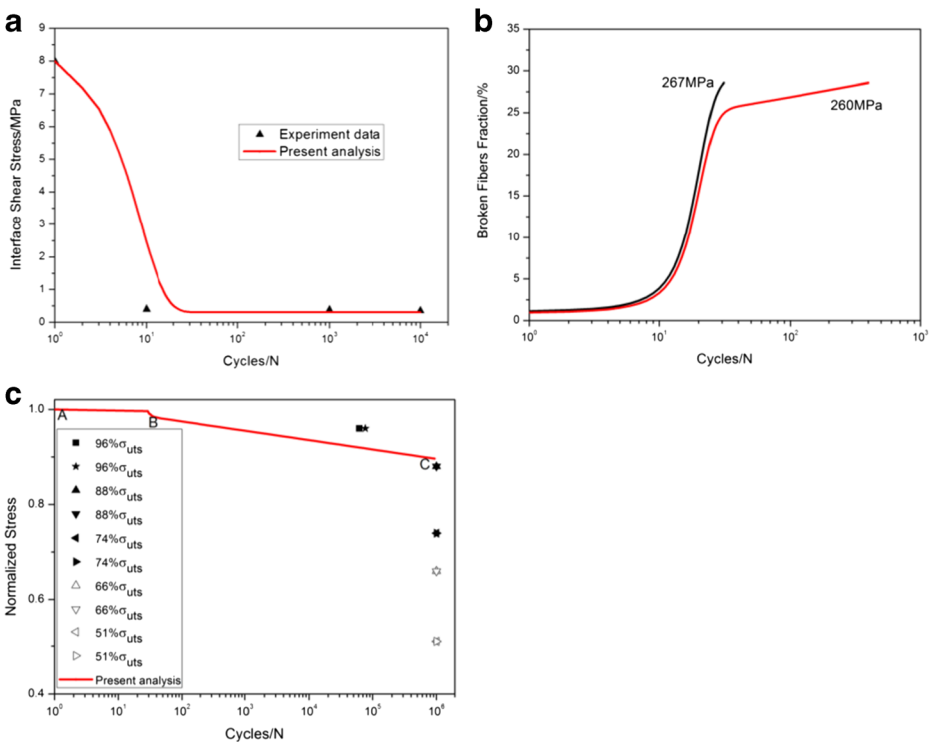


Fig. 1 a the interface shear stress versus applied cycles; b the fiber strength versus applied cycles; and c the fatigue life S–N curves of experimental data and present analysis for unidirectional C/SiC composite at room temperature

which the model parameters are given by $\tau_{i0}=6.1$ MPa, $\tau_{imin}=0.2$ MPa, $\omega=0.001$ and $\lambda=0.8$. The fiber strength degradation curve is predicted by Lee–Stinchcomb model [6], in which the model parameters are given by $p_1=0.02$ and $p_2=1.0$.

The broken fibers fraction under fatigue peak stress of $\sigma_{max}=240$ and 150 MPa corresponding to different number of applied cycles curve is illustrated in Fig. 2b, in which the broken fibers fraction increases with the increase of fatigue peak stress due to degradation of interface shear stress and fibers strength. Under fatigue peak stress of $\sigma_{max}=240$ MPa, the specimen fatigue failed after 5799 cycles. Under fatigue peak stress of $\sigma_{max}=150$ MPa, the specimen fatigue failed after 111,424 cycles. The broken fibers fraction versus applied cycles curve can be divided into two regions, i.e., (1) at the beginning of fatigue cycles, the broken fibers fraction increases rapidly due to degradation of interface shear stress and fibers strength; (2) when the interface shear stress approaches steady-state value, fibers failure is mainly controlled by fibers strength degradation, as shown in Fig. 2b.

The experimental and predicted fatigue life S–N curves of unidirectional C/SiC composite at 800 °C in air atmosphere are given in Fig. 2c, in which the fatigue life is greatly reduced compared with that at room temperature, which is mainly attributed to oxidation of PyC interphase or carbon fibers. The predicted fatigue life S–N curves can also be divided into two regions, i.e., (1) the A–B part is affected by degradation of interface shear stress and fibers strength; and (2) the B–C part is only affected by fibers strength degradation, as shown in Fig. 2c.

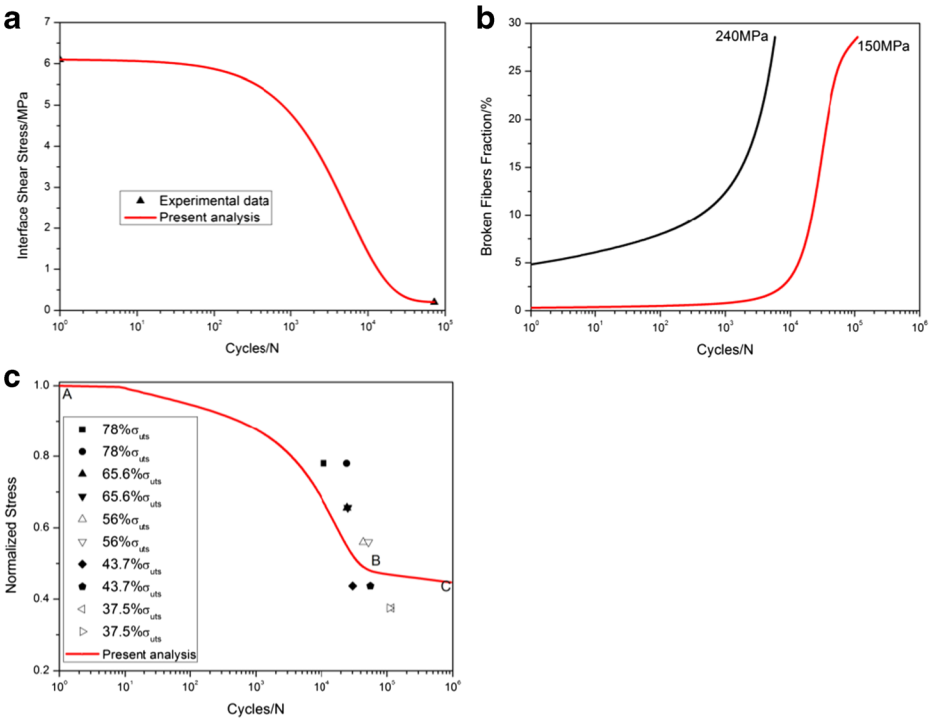


Fig. 2 **a** the interface shear stress versus applied cycles; **b** the fiber strength versus applied cycles; and **c** the fatigue life S–N curves of experiment data and present analysis for unidirectional C/SiC composite at 800 °C in air atmosphere

3.2 Cross-ply C/SiC Composite

3.2.1 Room Temperature

The interface shear stress of cross-ply C/SiC composite at room temperature has been estimated by comparing experimental fatigue hysteresis loss energy with theoretical computational values [9]. The interface shear stress versus applied cycles has been simulated by Evans–Zok–McMeeking model [7], as shown in Fig. 3a, in which the model parameters are given by $\tau_{i0}=6.2$ MPa, $\tau_{imin}=1.5$ MPa, $\omega=0.06$ and $\lambda=1.8$. The interface shear stress degrades from 6.2 MPa at the 1st cycle to 2 MPa at the 100th cycle. The fiber strength degradation curve is predicted by Lee–Stinchcomb model [6], in which the model parameters are given by $p_1=0.01$ and $p_2=0.8$.

The broken fibers fraction under fatigue peak stress of $\sigma_{max}=110$ and 108 MPa corresponding to different number of applied cycles curve is illustrated in Fig. 3b, in which the broken fibers fraction increases with the increase of fatigue peak stress. Under fatigue loading, the broken fibers fraction increases with applied cycles increasing due to degradation of interface shear stress and fibers strength. Under fatigue peak stress of $\sigma_{max}=110$ MPa, the specimen fatigue failed after 10 cycles. Under fatigue peak stress of $\sigma_{max}=108$ MPa, the specimen fatigue failed after 53 cycles. The broken fibers fraction versus applied cycles curve can be divided into two regions, i.e., (1) at the first 10 cycles, the broken fibers fraction

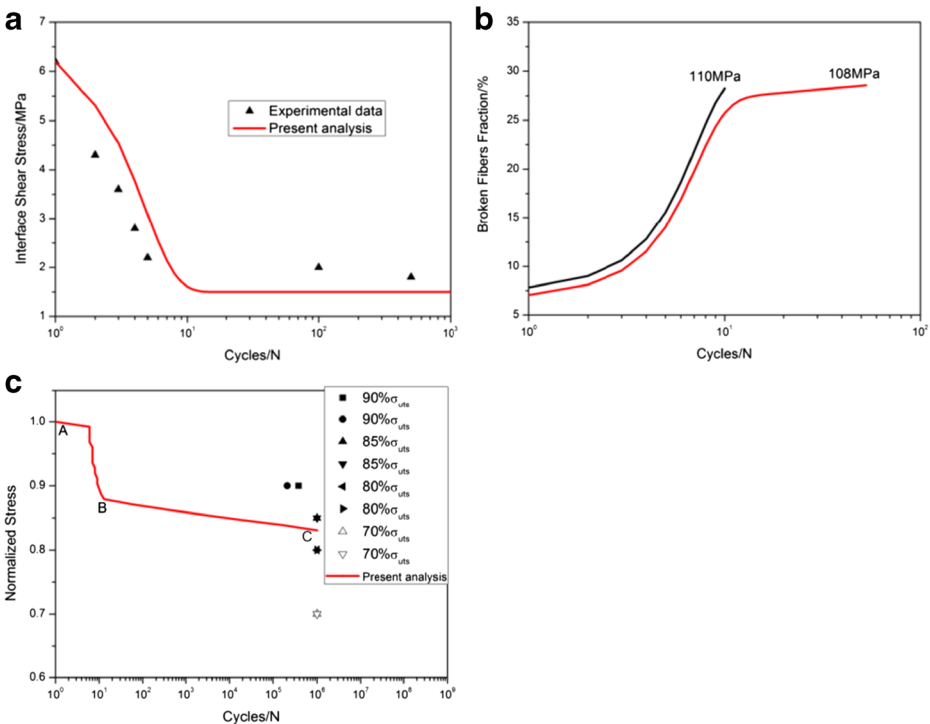


Fig. 3 a the interface shear stress versus applied cycles; b the fiber strength versus applied cycles; and c the fatigue life S–N curves of experimental data and present analysis for cross-ply C/SiC composite at room temperature

increases rapidly due to degradation of interface shear stress and fibers strength; and (2) when the interface shear stress approaches steady-state value, fibers failure is mainly controlled by fibers strength degradation, as shown in Fig. 3b.

The experimental and predicted fatigue life S–N curves of cross-ply C/SiC composite at room temperature are illustrated in Fig. 3c, in which the fatigue limit stress approaches 88 % of tensile strength. The predicted fatigue life S–N curves can be divided into two regions, i.e., (1) the A–B part is affected by the degradation of interface shear stress and fibers strength; and (2) the B–C part is only affected by fibers strength degradation, as shown in Fig. 3c.

3.2.2 Elevated Temperature

The interface shear stress of cross-ply C/SiC composite at an elevated temperature of 800 °C in air atmosphere has been estimated by comparing experimental fatigue hysteresis loss energy with theoretical computational values [9]. The interface shear stress versus applied cycles has been simulated by Evans–Zok–McMeeking model [7], as shown in Fig. 4a, in which the model parameters are given by $\tau_{i0}=5.5$ MPa, $\tau_{imin}=0.4$ MPa, $\omega=0.001$ and $\lambda=1.0$. The interface shear stress degrades from 5.5 MPa at the 1st cycle to 0.6 MPa at the 3600th cycle. The fiber strength degradation curve is predicted by Lee–Stinchcomb model [6], in which the model parameters are given by $p_1=0.02$ and $p_2=1.0$.

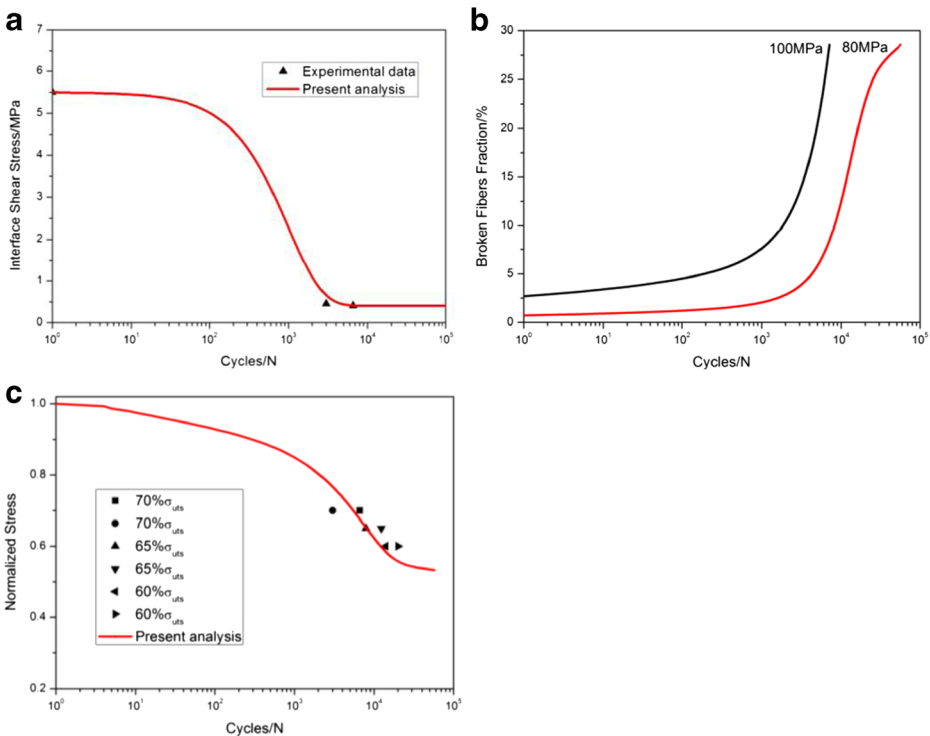


Fig. 4 a the interface shear stress versus applied cycles; b the fiber strength versus applied cycles; and c the fatigue life S–N curves of experimental data and present analysis for cross-ply C/SiC composite at 800 °C in air atmosphere

The broken fibers fraction under fatigue peak stress of $\sigma_{\max}=100$ and 80 MPa corresponding to different number of applied cycles curve is illustrated in Fig. 4b, in which the broken fibers fraction increases with the increase of fatigue peak stress. Under fatigue loading, the broken fibers fraction increases with the increase of applied cycles due to degradation of interface shear stress and fibers strength. Under fatigue peak stress of $\sigma_{\max}=100$ MPa, the specimen fatigue failed after 7116 cycles. Under fatigue peak stress of $\sigma_{\max}=80$ MPa, the specimen fatigue failed after 56,991 cycles. The broken fibers fraction versus applied cycles curve can be divided into two regions, i.e., (1) at the beginning of cyclic loading, the broken fibers fraction increases rapidly due to degradation of interface shear stress and fibers strength; and (2) when the interface shear stress approaches steady-state value, fibers failure is mainly attributed to fibers strength degradation, which makes the broken fibers fraction increase slowly, as shown in Fig. 4b.

The experimental and predicted fatigue life S–N curves of cross-ply C/SiC composite at an elevated temperature of 800 °C in air atmosphere are illustrated in Fig. 4c, in which the fatigue life of cross-ply C/SiC composite at 800 °C in air atmosphere is greatly reduced compared with that at room temperature, which is mainly attributed to oxidation of PyC interphase and carbon fibers. The predicted fatigue life S–N curves can be divided into two regions, i.e., (1) the A–B part is affected by degradation of interface shear stress and fibers strength; and (2) the B–C part is only affected by fibers strength degradation, as shown in Fig. 4c.

3.3 2.5D C/SiC Composites

3.3.1 Room Temperature

The interface shear stress of 2.5D C/SiC composite at room temperature has been estimated by comparing experimental fatigue hysteresis loss energy with theoretical computational values [9]. The interface shear stress versus applied cycles has been simulated by Evans–Zok–McMeeking model [7], as shown in Fig. 5a, in which the model parameters are given by $\tau_{i0}=20$ MPa, $\tau_{imin}=8$ MPa, $\omega=0.001$ and $\lambda=1.0$. The interface shear stress degrades from 20 MPa at the 1st cycle to 8 MPa at the 5000th cycle. The fiber strength degradation curve is predicted by Lee–Stinchcomb model [6], in which the model parameters are given by $p_1=0.02$ and $p_2=1.2$.

The broken fibers fraction under fatigue peak stress of $\sigma_{\max}=200$ and 180 MPa corresponding to different number of applied cycles curve is illustrated in Fig. 5b, in which the broken fibers fraction increases with the increase of fatigue peak stress. Under fatigue loading, the broken fibers fraction increases with applied cycles increasing due to degradation of interface shear stress and fibers strength. Under fatigue peak stress of $\sigma_{\max}=200$ MPa, the specimen fatigue failed after 832 cycles. Under fatigue peak stress of $\sigma_{\max}=180$ MPa, the specimen fatigue failed after 13,470 cycles. The broken fibers fraction versus applied cycles curve can be divided into two regions, i.e., (1) at the first 1000 cycles, the broken fibers fraction increases rapidly due to degradation of interface shear stress and fibers strength; (2) when the interface shear stress approaches steady-state value, fibers failure is mainly attributed to fibers strength degradation, which makes the broken fibers fraction increase slowly, as shown in Fig. 5b.

The experimental and predicted fatigue life S–N curves of 2.5D C/SiC composite at room temperature are illustrated in Fig. 5c. The fatigue limit stress approaches 70 % of tensile strength. The predicted fatigue life S–N curve can be divided into two regions, i.e., (1) the A

–B part is mainly controlled by degradation of interface shear stress and fibers strength; and (2) the B–C part is only affected by fibers strength degradation, as shown in Fig. 5c.

3.3.2 Elevated Temperature

The interface shear stress of 2.5D C/SiC composite at an elevated temperature of 800 °C in air atmosphere has been estimated by comparing experimental fatigue hysteresis loss energy with theoretical computational values [9]. The interface shear stress versus applied cycles has been simulated by Evans–Zok–McMeeking model [7], as shown in Fig. 6a, in which the model parameters are given by $\tau_{i0}=20$ MPa, $\tau_{imin}=5$ MPa, $\omega=0.008$ and $\lambda=1.2$. The interface shear stress degrades from 20 MPa at the 1st cycle to 5 MPa at the 3600th cycle. The fiber strength degradation is predicted by Lee–Stinchcomb model [6], in which the model parameters are given by $p_1=0.03$ and $p_2=1.2$.

The broken fibers fraction under fatigue peak stress of $\sigma_{max}=260$ and 180 MPa corresponding to different number of applied cycles curve is illustrated in Fig. 6b. The broken fibers fraction increases with the increase of fatigue peak stress. Under fatigue loading, the broken fibers fraction increases with applied cycles increasing due to degradation of interface shear stress and fibers strength. Under fatigue peak stress of $\sigma_{max}=260$ MPa, the specimen fatigue failed after 276 cycles. Under fatigue peak stress of $\sigma_{max}=180$ MPa, the specimen fatigue failed after 6981 cycles. The broken fibers fraction versus applied cycles curve can be divided

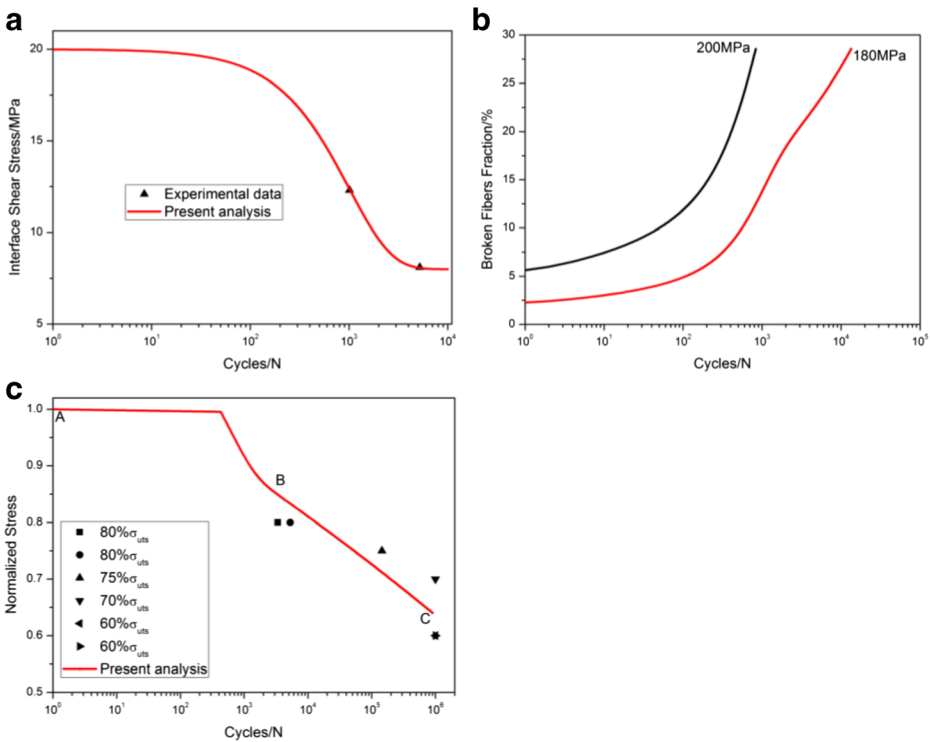


Fig. 5 a the interface shear stress versus applied cycles; b the fiber strength versus applied cycles; and c the fatigue life S–N curves of experimental data and present analysis for 2.5D C/SiC composite at room temperature

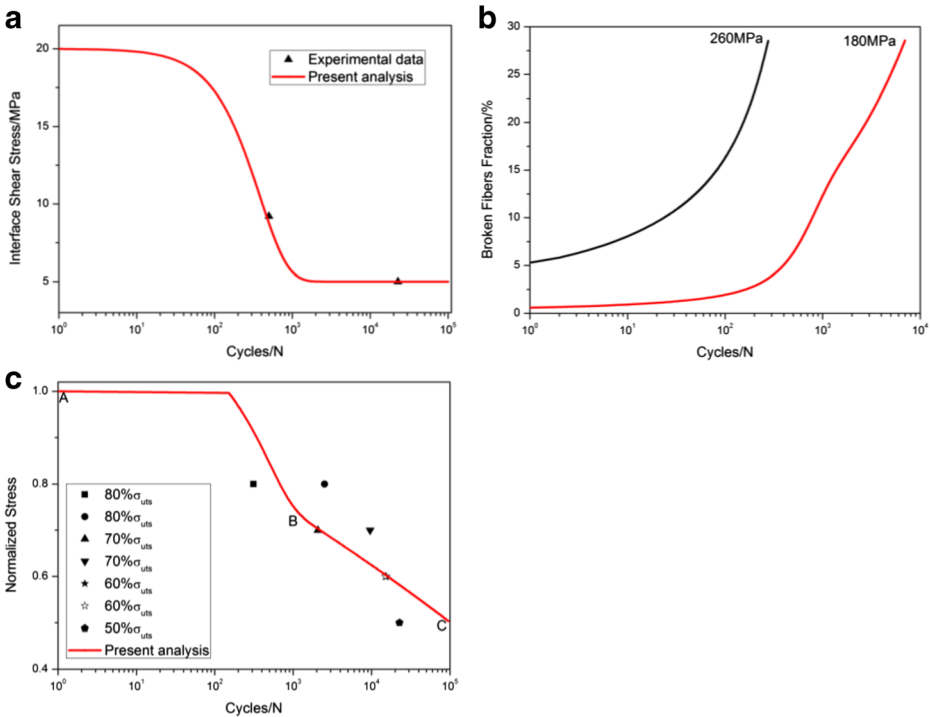


Fig. 6 **a** the interface shear stress versus applied cycles; **b** the fiber strength versus applied cycles; and **c** the fatigue life S–N curves of experimental data and present analysis for 2.5D C/SiC composite at an elevated temperature of 800 °C in air atmosphere

into two regions, i.e., (1) at the first 3000 cycles, the broken fibers fraction increases rapidly due to degradation of interface shear stress and fibers strength; and (2) when the interface shear stress approaches steady-state value, fibers failure is mainly attributed to fibers strength degradation, which makes the broken fibers fraction increase slowly, as shown in Fig. 6b.

The experimental and predicted fatigue life S–N curves of 2.5D C/SiC composite at an elevated temperature of 800 °C in air atmosphere are illustrated in Fig. 6c, in which the fatigue life of 2.5D C/SiC composite at 800 °C in air atmosphere is greatly reduced compared with that at room temperature, mainly attributed to oxidation of PyC interphase and carbon fibers. The predicted fatigue life S–N curves can be divided into two regions, i.e., (1) the A–B part is mainly controlled by degradation of interface shear stress and fibers strength; and (2) the B–C part is only affected by fibers strength degradation, as shown in Fig. 6c.

4 Conclusions

The fatigue life S–N curves of unidirectional, cross-ply and 2.5D C/SiC composite at room temperature and 800 °C in air atmosphere have been predicted. By comparing experimental fatigue hysteresis loss energy with theoretical computational values, the interface shear stress has been estimated for different fiber preforms, test conditions, fatigue peak stresses and number of applied cycles. The Evans–Zok–McMeeking model parameters for interface shear

stress degradation have been determined by fitting the values of estimated interface shear stress. The broken fibers fraction versus applied cycles curve was predicted, in which the broken fibers fraction increases rapidly at the initial stage of fatigue loading; when the interface shear stress approaches steady-state value, fibers failure is mainly attributed to fibers strength degradation, which makes the broken fibers fraction increase slowly. At elevated temperature, the degradation of fibers strength due to oxidation leads to the fatigue life greatly reduced compared with that at room temperature.

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Compliance with Ethical Standards

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Conflict of Interest The author declares that he has no conflict of interest.

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