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Meso-scale progressive damage modeling and life prediction of 3D braided composites under fatigue tension loading

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Abstract: 3D braided composites have broad potential applications in the high-tech industries because of their superior mechanical properties. Fatigue is an essential design factor for their use in those engineering applications. The fatigue damage accumulation during cyclic loading should be involved in the numerical models in order to predict the fatigue life accurately. In this paper, a unit-cell based finite element model in conjunction with continuum damage mechanics (CDM) is developed for simulating the fatigue damage evolution process and predicting the fatigue life of 3D braided composites under fatigue tension loading. This meso-scale fatigue modeling, including stress analysis, failure criteria and material property degradation scheme, is implemented via a user-material subroutine UMAT based on ABAQUS/Standard platform with FORTRAN code. The fatigue damage initiation and propagation processes of 3D braided composites with typical braiding angles on the unit-cell model as a function of number of cycles are presented in detail. The fatigue life of 3D braided composites is predicted from the computed *S-N* curve and the stiffness degradation process is also investigated. The obtained numerical results indicate that the present model can provide a suitable reference to the numerical study of the fatigue issues in other textile composites.

Keywords: 3D braided composites; unit-cell; progressive fatigue damage; fatigue life prediction; finite element modeling

1 Introduction

The past few decades have witnessed the accelerated usage of advanced composite materials in the aerospace, automotive, wind-energy, sports and other high-tech industries. As a kind of new lightweight textile composites, 3D braided composites own many dominant advantages over laminated composites, such as enhanced out-of-plane performance, better structural integrity, higher damage tolerance and lower production costs. Thus, 3D braided composites are convinced to have broad potential applications in the high-tech industries. Actually, during the service in these applications, 3D braided composites are frequently subjected to cyclic and fluctuating loading conditions, which could eventually cause fatigue damage in the composite structures. Because of the lack of reliable numerical modeling technique, large safety factors are always selected and lots of experimental tests have to be conducted in the design process. In this condition, the great weight-saving potential of 3D braided composites would not be adequately realized, especially in the primary loading-bearing structures. However, thus far, most of the existing numerical works are focused on the analysis of static mechanical behavior and failure mechanisms [1-10]. Therefore, it is of great value to propose a fatigue model to predict the damage failure and fatigue life of 3D braided composites within the frame of finite element simulation.

The available fatigue models for composite materials can be classified into three major categories: fatigue life models, phenomenological models and progressive damage models [11-13]. Fatigue life model generally utilizes an empirical *S-N* curve combined with a proposed fatigue failure criterion to determine the fatigue life of the composite specimen. However, the damage accumulation process is not considered in such fatigue life model. Phenomenological model includes the depiction of damage during fatigue loading by introducing an evolution law to describe the degradation of stiffness and strength properties of the composite specimen. Progressive damage model is currently the most advanced model because it has the ability to predict the fatigue life as well as the material properties degradation in the composite specimen by using different damage variables related to corresponding damage mechanisms.

Shokrieh and Lessard [14, 15] initially established the frame of progressive fatigue damage model (PFDM) to simulate the mechanical behavior of composite laminates under fatigue loading conditions. PFDM is a general frame and it is independent of the configuration of composite structures. This numerical model is able to determine the state of damage at any load levels and number of cycles from damage initiation, propagation to final failure. That is to say, the model is able to predict the damage mechanism and fatigue life under general fatigue loading conditions. Because of the huge advantage of PFDM, it had been adopted by many researchers to predict the fatigue life and damage evolution of different types of composite structures. In Refs. [16-18], they reported similar finite element models to predict the fatigue life and fatigue damage evolution in composite laminates with different stacking sequences on the basis of the fatigue characteristics data of unidirectional composites in longitudinal, transverse and in-plane shear directions respectively. Wu and Gu [19] and Sun et al. [20] proposed a microstructure computational approach on fatigue behavior prediction of 3D braided and woven composites under three-point low-cycle bending. The stiffness degradation and damage morphologies were obtained from finite element modeling and compared with those from experimental tests. Wicaksono and Chai [21] established a stiffness decay model to study the static and fatigue responses of a woven composite I-beam structure in four point bending. The numerical results of the static response, fatigue response, fatigue life and stiffness decay predictions were compared with the experimental data and validated the proposed model. Bhuiyan and Fertig [22] utilized a kinetic theory of fracture to model the fatigue behavior in a 2D woven composite representative volume element (RVE). The progressive fatigue damage process in the constituents of woven RVE was simulated and the *S-N* curves for the tension-tension and shear load cases were determined. Xu et al. [23, 24] developed a PFDM to simulate the fatigue damage initiation and evolution based on a unit-cell of 2D textile composites under tension-tension loading. In the unit-cell model, *S-N* curves of a unidirectional composite from the complete fatigue tests were set as the input for impregnated yarns. A good agreement between the numerical results and available experimental data was obtained. Similar works were also conducted by Qiu et al. [25] and Hao et al. [26] to predict the fatigue life and simulate the progressive fatigue damage process of 2.5D woven and 3D 4-directional braided composites subjected to fatigue tension loading.

The microstructure of 3D braided composites is particularly complicated, and it shows intensive inhomogeneity and anisotropy, which results in considerable difficulties in the fatigue properties prediction and damage mechanism analysis. Up to now, the numerical study on the fatigue mechanical behavior of 3D braided composites is extremely limited. On the other hand, PFDM is frequently used in the simulation of fatigue behavior of laminated composites while the feasibility and effectiveness of PFDM in predicting fatigue properties of composites with complex microstructure, such as 3D braided composites, have not been studied well.

The main objective of the present work is to propose a meso-scale finite element model based on the frame of PFDM, which aims to predict the damage evolution and fatigue life of 3D braided composites subjected to fatigue tension loading. In the unit-cell model, the stress analysis, failure analysis and material property degradation scheme, which are the key points in the fatigue failure analysis and fatigue life prediction, are numerically implemented. By accomplishing it, a meso-scale finite element model using a user-material subroutine UMAT based on finite element package ABAQUS/Standard is thus developed. The whole process of fatigue damage initiation, propagation and final failure is executed, and the damage mechanisms in this process are revealed in detail. Moreover, the *S-N* curves are established in the tension fatigue loading cases and the corresponding stiffness degradation with number of cycles is also examined.

The rest of the paper is structured as follows. In Section 2, the formulation of progressive fatigue damage model is presented, in which the fatigue failure criteria and anisotropic damage model are described. The meso-scale finite element modeling is then presented in Section 3. In this section, the periodic boundary condition, the material properties of constituents, unit-cell homogenization, and the implementation of fatigue failure modeling are given. In Section 4, the obtained numerical results and detailed discussion are given. Some conclusions drawn from the study are given in Section 5.

2 Progressive fatigue damage model

The damage process of composite structures under general fatigue loading conditions can be simulated by damage model, which consists of fatigue failure criteria and material property degradation scheme. In this paper, the unit-cell model of 3D braided composites is considered consisting of braiding yarns and resin matrix. The resin matrix is assumed to be isotropic material; and the braiding yarns are regarded as transversely isotropic unidirectional composites in the local *L-T-Z* coordinate where *L*, *T* and *Z* axes indicate the longitudinal and two transverse directions.

2.1 Fatigue failure criteria

In the unit-cell model, 3D Hashin failure criteria [27] and maximum stress criteria are applied to determine the fatigue failure of braiding yarns and matrix by using fatigue residual strength instead of static strength in the denominators of failure criteria.

3D Hashin criteria use several failure indexes to consider the distinct failure modes of braiding yarn, namely

Yarn tensile fatigue failure in *L* direction ($\sigma_L \geq 0$)

$$\varphi_{Lt} = \left(\frac{\sigma_L}{F_L^t(n,\sigma,\kappa)} \right)^2 + \alpha \left(\frac{\sigma_{LT}}{S_{LT}(n,\sigma,\kappa)} \right)^2 + \alpha \left(\frac{\sigma_{LZ}}{S_{LZ}(n,\sigma,\kappa)} \right)^2 \geq 1 \tag{1}$$

Yarn compressive fatigue failure in *L* direction ($\sigma_L < 0$)

$$\varphi_{Lc} = \left(\frac{\sigma_L}{F_L^c(n,\sigma,\kappa)} \right)^2 \geq 1 \tag{2}$$

Yarn tensile and shear fatigue failure in *T* and *Z* direction ($\sigma_T + \sigma_Z \geq 0$)

$$\begin{aligned} \varphi_{T(Z)t} = & \left(\frac{\sigma_T + \sigma_Z}{F_T^t(n,\sigma,\kappa)} \right)^2 + \left(\frac{1}{S_{TZ}^2(n,\sigma,\kappa)} \right) \left(\sigma_{TZ}^2 - \sigma_T \sigma_Z \right) \\ & + \left(\frac{\sigma_{LT}}{S_{LT}(n,\sigma,\kappa)} \right)^2 + \left(\frac{\sigma_{LZ}}{S_{LZ}(n,\sigma,\kappa)} \right)^2 \geq 1 \end{aligned} \tag{3}$$

Yarn compressive and shear fatigue failure in *T* and *Z* direction ($\sigma_T + \sigma_Z < 0$)

$$\begin{aligned} \varphi_{T(Z)c} = & \left(\frac{\sigma_T + \sigma_Z}{2S_{TZ}(n,\sigma,\kappa)} \right)^2 + \left(\frac{\sigma_T + \sigma_Z}{F_T^c(n,\sigma,\kappa)} \right) \left[\left(\frac{F_T^c}{2S_{TZ}(n,\sigma,\kappa)} \right)^2 - 1 \right] + \frac{1}{S_{TZ}^2(n,\sigma,\kappa)} \left(\sigma_{TZ}^2 - \sigma_T \sigma_Z \right) \\ & + \left(\frac{\sigma_{LT}}{S_{LT}(n,\sigma,\kappa)} \right)^2 + \left(\frac{\sigma_{LZ}}{S_{LZ}(n,\sigma,\kappa)} \right)^2 \geq 1 \end{aligned} \tag{4}$$

In the above equations, φ is the failure index related to corresponding failure mode; α is the shear failure coefficient utilized to determine the contribution of shear stresses on the yarn tensile fatigue failure in *L* direction, and α=0.5 is used in this paper. $F_L^t(n,\sigma,\kappa)$ and $F_L^c(n,\sigma,\kappa)$ are the longitudinal tensile and compressive residual strengths of braiding yarn; $F_T^t(n,\sigma,\kappa)$ and $F_T^c(n,\sigma,\kappa)$ are the transverse tensile and compressive residual strengths; $S_{LT}(n,\sigma,\kappa)$, $S_{LZ}(n,\sigma,\kappa)$ and $S_{TZ}(n,\sigma,\kappa)$ are the *LT*, *LZ* and *TZ* shear residual strengths, respectively. All the residual strengths properties of braiding yarn are functions of n, σ and κ, which are number of cycles, stress state and stress ratio, respectively.

Maximum stress criteria use two failure indexes to define the tensile and compressive failure of matrix, namely

$$\varphi_{Mt} = \left| \frac{\sigma_1^t}{F_m^t(n,\sigma,\kappa)} \right| \geq 1 \tag{5}$$

$$\varphi_{Mc} = \left| \frac{\sigma_3^c}{F_m^c(n,\sigma,\kappa)} \right| \geq 1 \tag{6}$$

where σ_1^t and σ_3^c are the maximum tensile and compressive stresses of matrix; $F_m^t(n,\sigma,\kappa)$ and $F_m^c(n,\sigma,\kappa)$

are tensile and compressive residual strengths of matrix.

2.2 Material property degradation scheme

The material property degradation of 3D braided composites under fatigue loading has two schemes: sudden property degradation and gradual property degradation. For the elements in the unit-cell model, if the fatigue failure criteria are triggered, the element is failed and the sudden property degradation will be performed according to the failure modes. On the other hand, if the fatigue failure criteria are not activated, the element in such circumstance is not to be failed but the stiffness and strength gradual degradation should be conducted due to fatigue cycles.

2.2.1 Anisotropic damage model

Murakami's damage tensor [28] is adopted to characterize the damage modes of braiding yarn and matrix, which uses three principal damage variables to express the damage state, namely

$$D = \sum_i D_i n_i \otimes n_i \quad (i = L, T, Z) \tag{7}$$

where D_i and n_i are the principal value and principle unit vector of the damage tensor.

For the damaged material, the effective stress is defined as

$$\sigma^* = \frac{1}{2}[(I-D)^{-1}\sigma + \sigma(I-D)^{-1}] = M(D)\sigma \tag{8}$$

Here σ^* is symmetric and $M(D)$ is a transformation matrix.

Next, the constitutive equation of the damaged material is given by

$$\varepsilon = H(D)\sigma \tag{9}$$

where $H(D)$ is the damaged compliance matrix and can be determined by the notion of energy identification, namely

$$H(D) = (M(D))^T : C_0^{-1} : M(D) \tag{10}$$

where C_0 is the undamaged stiffness matrix.

This, in turn, leads to the damaged stiffness matrix, which is the function of elastic constants and principal values of damage tensor, namely [29]

$$C(D) = H^{-1}(D) = \begin{Bmatrix} b_L^2 C_{11} & 0 & 0 & 0 & 0 & 0 \\ b_L b_T C_{12} & b_T^2 C_{22} & 0 & 0 & 0 & 0 \\ b_L b_Z C_{13} & b_T b_Z C_{23} & b_Z^2 C_{33} & 0 & 0 & 0 \\ & & & b_{TZ} C_{44} & 0 & 0 \\ & sym & & & b_{ZL} C_{55} & 0 \\ & & & & & b_{LT} C_{66} \end{Bmatrix} \tag{11}$$

In the above equation,

$$b_L = 1 - D_L, \; b_T = 1 - D_T, \; b_Z = 1 - D_Z$$

$$b_{TZ} = \left(\frac{2b_T b_Z}{b_T + b_Z}\right)^2, \; b_{ZL} = \left(\frac{2b_Z b_L}{b_Z + b_L}\right)^2, \; b_{LT} = \left(\frac{2b_L b_T}{b_L + b_T}\right)^2$$

C_{ij} is the component of undamaged stiffness matrix.

2.2.2 Sudden property degradation

For braiding yarn, the principal damage variables in L, T, and Z direction are defined by

$$D_L = \max(d_{Lt}, d_{Lc}) \tag{12}$$

$$D_T = \max(d_{Tt}, d_{Tc}) \tag{13}$$

$$D_Z = \max(d_{Zt}, d_{Zc}) \tag{14}$$

For matrix, one has

$$D_M = D_L = D_T = D_Z = \max(d_{Mt}, d_{Mc}) \tag{15}$$

In the above equations, $d_{\mathrm{I}}(\mathrm{I} = Lt, Lc, Tt, Tc, Zt, Zc)$ are the damage variables corresponding to distinct damage modes of braiding yarn; d_{Mt} and d_{Mc} are the damage variables corresponding to tension and compression damage of matrix, respectively.

The damage variables range from 0 to 1.0 according to damage state. Here, 0 represents the initial undamaged state and 1.0 indicates the completely damaged state. In this paper, in order to eliminate the matrix singularity of computation in the sudden stiffness degradation and considering the specific damage modes, the principle values of damage tensor equal to 1.0 need to be modified. For the failed elements of braiding yarn, if the failure is fiber controlled, principal damage variable D_L will be set, for instance, as 0.99; if the failure is matrix controlled, principal damage variable D_T or D_Z will be set as 0.95 according to the damage direction. For the failed elements of matrix, D_M will be set as 0.90.

2.2.3 Gradual property degradation

Under fatigue loading condition, the composite structure is loaded by a stress state which is less than the static strength of the material. By continuously increasing the number of cycles, the material properties degrade gradually and eventually reach a level where distinct failure modes can be detected by the proposed fatigue failure criteria [14].

For the braiding yarn, the residual strength and stiffness models for unidirectional composite proposed by Shokrieh and Lessard [14, 15] are employed, in which the effects of stress state and stress ratio have been considered. It should be pointed out that due to the different distortion and bending state of braiding yarn in 3D braided composites compared to that of unidirectional composite, some computational errors may be introduced to the simulation model with this simplified assumption.

The residual strength $R(n,\sigma,\kappa)$ and residual stiffness $E(n,\sigma,\kappa)$ are expressed as

$$R(n,\sigma,\kappa) = \left[1 - \left(\frac{\log(n) - \log(0.25)}{\log(N) - \log(0.25)}\right)^{\beta}\right]^{1/\varphi} \left(R_s - \sigma\right) + \sigma \tag{16}$$

$$E(n,\sigma,\kappa) = \left[1 - \left(\frac{\log(n) - \log(0.25)}{\log(N) - \log(0.25)}\right)^{\lambda}\right]^{1/\eta} \left(E_s - \frac{\sigma}{\varepsilon_f}\right) + \frac{\sigma}{\varepsilon_f} \tag{17}$$

In the above equations, R_s and E_s are the static strength and stiffness; ε_f and σ are the critical strain at failure and maximum applied stress; n and N are number of cycles and fatigue life; φ and β are curve fitting parameters for strength degradation; λ and η are curve fitting parameters for stiffness degradation.

In order to make the gradual property degradation model applicable to arbitrary stress ratio and stress state, the normalized fatigue life model developed by Adam et al. [30] was adopted by Shokrieh and Lessard [14, 15] to predict the fatigue life of unidirectional composite.

Under longitudinal and transverse fatigue loading, the normalized fatigue life prediction model can be expressed as

$$u = \frac{\ln(a/f)}{\ln[(1-g)(c+g)]} = A + B\log N \tag{18}$$

Under shear fatigue loading condition, the normalized fatigue life prediction model can be modified as

$$u = \log\frac{\ln(a/f)}{\ln[(1-g)(1+g)]} = A + B\log N \tag{19}$$

In the above equations, $a = \sigma_a / \sigma_t$, $g = \sigma_m / \sigma_t$, $c = \sigma_c / \sigma_t$; $\sigma_a = (\sigma_{\max} - \sigma_{\min})/2$ is alternating stress; $\sigma_m = (\sigma_{\max} + \sigma_{\min})/2$ is mean stress; $\sigma_{\max}$ and $\sigma_{\min}$ are maximum and minimum applied stresses; σ_t and σ_c are tensile and compressive strengths of composite; *u* and *f* are curve fitting parameters.

In this paper, since the stiffness and strength of 3D braided composites are mainly determined by fiber braiding yarns and the residual material property data for resin matrix are not available now, the gradual property degradation of pure resin matrix under fatigue loading is not considered in the simulation.

3 Finite element modeling

3.1 Meso-scale finite element model and boundary conditions

A unit-cell structural model of 3D braided composites developed by Xu and Xu [31] is adopted here as a basis for the fatigue damage simulation, as shown in Fig. 1(a). The cross-section shape of the braiding yarns is assumed as octagon containing an inscribed ellipse. The relationship between the major and minor radii of the ellipse, *a* and *b*, is determined by

$$a = \sqrt{3} b \cos\gamma \tag{20}$$

where γ is the interior braiding angle and it can be determined by the braiding angle α on the surface of composite specimen as

$$\tan\gamma = \sqrt{2}\tan\alpha \tag{21}$$

According to the geometry relation, we have

$$W = T = 4\sqrt{2} b \tag{22}$$

$$h = 8b / \tan\gamma \tag{23}$$

$$S_b = 8(\sqrt{3}-1) b^2 \cos\gamma \tag{24}$$

$$V_f = \frac{V_b}{V}\kappa_b = \frac{4hS_b / \cos\gamma}{W \times T \times h}\kappa_b = (\sqrt{3}-1)\kappa_b \tag{25}$$

In the above equations, *W*, *T*, *h*, *V* are the width, thickness, height and volume of the unit-cell models, respectively; S_b and κ_b are the cross-sectional area and yarn packing factor of braiding yarn; V_f is the fiber volume fraction of braided composites.

Since the finite element modeling of fatigue damage is based on the unit-cell model, the periodic boundary conditions should be employed to replicate the repeating nature of composite structures. Therefore, identical mesh at opposite surfaces (periodic mesh) of the unit-cell needs to be ensured in the meshing process. Due to the complicated microstructure of 3D braided composites, periodic mesh generation is a very challenging task. Herein, the built-in 3D solid tetrahedral element (C3D4) available in ABAQUS/Standard package is selected to discretize the braiding yarns and matrix in the unit-cell model because of its excellent geometry adaptability. In this analysis, the interfaces between the braiding yarns and matrix are assumed to be perfectly bonded and co-nodes mesh is adopted. The finite element mesh of unit-cell of 3D braided composites is displayed in Fig. 1(b).

It is known that either force or displacement can be used as the applied load when employing the periodic boundary conditions in the unit-cell based simulation. Here in this study, the displacement loading mode is used in the static analysis to obtain the static tensile strength while the force loading mode is applied in the fatigue analysis to predict the fatigue life. Periodic boundary conditions are employed by setting the displacement constraint equations between the related nodes on the paired surfaces, edges and corners of the unit-cell model. The detailed application process can be found in our previous work [32].

3.2 Material properties of constituents and unit-cell homogenization

Restricted by the current experimental conditions, it is very difficult to obtain the fatigue degradation rule of braiding yarn in the main directions directly through fatigue tests. In the meso-scale model, the braiding yarn containing thousands of fibers is regarded as unidirectional composite after resin impregnation. Therefore, the fatigue performance of braiding yarn can be replaced by that of unidirectional composite. The fatigue behavior of the braiding yarn is described by the fatigue residual stiffness and strength models in the main directions of unidirectional composite. For the current simulation, the material properties of braiding yarn and matrix are listed in Table 1, and the PFDM parameters of unidirectional composite cited from Ref. [15] are adopted and summarized in Table 2.

In this paper, the unit-cell homogenization approach is utilized to attain the macroscopic mechanical properties of 3D braided composites. The average stresses $\bar{\sigma}_{ij}$ and strains $\bar{\varepsilon}_{ij}$ in the unit-cell can be computed by

$$\bar{\sigma}_{ij} = \frac{1}{V}\int_V \sigma_{ij} dV\ ,\quad \bar{\varepsilon}_{ij} = \frac{1}{V}\int_V \varepsilon_{ij} dV \tag{26}$$

where V is volume of the unit-cell.

3.3 Implementation of fatigue failure modeling

3.3.1 Basic assumptions

In order to improve the computational efficiency and save the computer resource, two main assumptions [16] have been made to simulate the fatigue loading in the meso-scale finite element model. (a) During each loading cycle, damage development in the unit-cell only happens at maximum and minimum fatigue stresses. (b) For the chosen cycle jumps, only gradual degradation of the material properties is involved and sudden degradation is excluded.

In fatigue loading boundary condition, the stress state of the unit-cell under minimum fatigue stress is equal to that under maximum fatigue stress multiply by the stress ratio R. For the tension-tension fatigue loading with R=0.1 in this paper, only the maximum fatigue load is needed to be applied according to the first assumption. The second assumption is made to involve the degradation of material properties in a specific cycle jump and then perform a new failure analysis and possible sudden degradation. Xu et al. [23] introduced the predefined cycle jump as $N_j=10^{n/m}-10^{(n-1)/m}$, where n is the step number and m is a predetermined positive integer, in the fatigue damage simulation of 2D textile composites and validated that the finite element model using this cycle jump (m=4) is enough to obtain a convergent solution for fatigue modulus and fatigue life. In this paper, the predefined cycle jump (m=10) is adopted. That is, the fatigue analysis is evaluated at cycle numbers $N=10^{0.1i}$, where i is a natural number.

3.3.2 Fatigue failure analysis process

The damage constitutive theory of constituents and progressive damage simulation approach are implemented in ABAQUS/Standard through user-defined material subroutine UMAT. The meso-scale modeling consists of two computational modules: static strength prediction and fatigue failure analysis. Fig. 2 presents the flow chart of the whole progressive damage analysis process. The meso-scale finite element model must first be established by introducing the structural parameters and material properties, and then the periodic boundary conditions need to be employed. As shown in Fig. 2(a), for the static strength prediction, the displacement loading mode is applied. During each load increment, the stress analysis and failure analysis are performed at the Gauss integration points of the elements. If there is no element failure found, a displacement load increment is applied to perform a new stress analysis. Once the failure criterion is satisfied, the sudden stiffness reduction is carried out by updating the damage variables corresponding to failure modes. Subsequently, it is necessary to determine whether the eventual failure happens. If the material is not yet finally failed, the stress analysis needs to be performed repeatedly. If the eventual failure is reached, the static analysis is over and the static strength can be obtained from the predicted stress-strain curve.

As shown in Fig. 2(b), for the fatigue failure analysis, the force loading mode is employed. Stress analysis is performed based on the maximum fatigue stress level. The stress state is examined and the failure analysis is performed by Hashin failure criteria for braiding yarn elements and maximum stress criteria for matrix elements. If an element has failed, the sudden stiffness degradation considering the specific damage mode will be conducted. At this time, if the final fatigue failure is not reached, stress analysis is needed to be performed again at the maximum fatigue stress level. If the final fatigue failure criterion is satisfied, the current number of cycles is adopted as the fatigue life of 3D braided composites and the fatigue analysis stops. On the other hand, if there is no sudden failure mode in the element, it is necessary to determine whether the fatigue limit is reached. If the number of cycles smaller than the fatigue limit, the gradual degradation of stiffness and strength properties of braiding yarn elements is implemented and the selected cycle jump is applied to perform new stress analysis again. If the fatigue limit is reached before the final fatigue failure, the fatigue life of the material at the stress level is defined as fatigue limit and the fatigue analysis ends.

3.3.3 Final failure criterion

In order to accurately predict the fatigue life of 3D braided composites, the final failure criterion which determines the ultimate failure of the unit-cell is necessary. Under fatigue loading condition, when the damage develops to a certain extent, 3D braided composites cannot bear the further load and the final failure of the composite structure happens. In the static analysis, the static strength (final failure point) is defined as the maximum stress value of the predicted stress-strain curve; however, in the fatigue analysis, the force loading boundary condition is fixed and the final failure criterion cannot be determined from the stress-strain curve.

It is known that for 3D braided composites, the final failure always happens due to extensive damage modes in the braiding yarns. In the finite element simulation, these extensive damage modes will lead to no convergence of computation. In this paper, it is assumed that the final fatigue failure occurs when the composite structure can no longer bear the fixed force loading or the finite element simulation cannot be convergent.

4 Numerical results and discussion

In this section, two 3D braided composite specimens with typical braiding angles are adopted to conduct the progressive fatigue damage simulation. In order to guarantee the convergence of the computation, performing a mesh sensitivity analysis is necessary. In this study, the meso-scale finite element model of specimen 1 with a small braiding angle 19.2^{o} consists of 31, 943 nodes and 129, 686 C3D4 elements, and that of specimen 2 with a large braiding angle 36.6^{o} consists of 11, 143 nodes and 40, 811 C3D4 elements, which are fine enough to provide the convergence calculation results. The structural parameters of the unit-cell models of the specimens are provided in Table 3.

4.1 Prediction of static strength

In the static analysis, the displacement loading mode is applied to simulate the damage evolution process and predict the stress-strain curve of 3D braided composites under axial tension loading. Fig. 3 presents the computed stress-strain curves and corresponded element damage percentage of yarns and matrix in the tension process. The element damage percentage is calculated via dividing the damaged element number by the corresponding element number of yarns and matrix in the unit-cell model. In the simulation process, it is found that the damaged elements of some modes are very few. For concision, only the main damage modes are given in Fig. 3.

As shown in Fig. 3(a), for specimen 1 with a small braiding angle, the stress-strain curve keeps approximately linear before reaching the peak stress and then decreases rapidly resulting in no convergence of computation, which indicates the brittle breaking characteristics. The predicted static tensile strength is 729.8 MPa and the main failure mode is yarn *L* tensile failure and matrix cracking. *T* compressive shear and *Z* tensile shear failure modes also arise in some yarn elements but the quantity is relatively small. As the increase of strain loading, matrix cracking occurs first in the yarn/matrix contact edges and propagates rapidly along the longitudinal and transverse directions of braiding yarn. Yarn *L* tensile failure mode appears when $\overline{\varepsilon}_z = 1.26\%$ and stimulates the yarn *T* compressive shear and *Z* tensile shear failure modes. Overall, yarn *L* tensile failure controls the final tension failure and determines the static tensile strength of specimen 1.

For specimen 2 with a large braiding angle as shown in Fig. 3(b), the stress-strain curve also presents good linear feature before reaching the peak stress and then decreases gradually. It is interesting to see that the convergence problem found in specimen 1 is not the case here. The predicted static tensile strength is 128.0 MPa and the main failure modes are yarn *T* compressive shear, yarn *Z* tensile shear failure and matrix cracking. Yarn *L* tensile failure mode is not observed in the whole simulation process. With the increasing of strain loading, yarn *T* compressive shear failure occurs first in yarn/yarn contact zones and propagates gradually along the transverse direction of the braiding yarn. Yarn *Z* tensile shear failure appears following the *T* compressive shear failure closely, and the expansion trend is also similar. Matrix cracking initiates when $\overline{\varepsilon}_z = 0.81\%$ and increases sharply as strain loading increase. Generally, the final static failure of specimen 2 can be attributed to the accumulation of various damage modes.

Once the stress-strain curves reach the peak stresses, the test specimens always tend to exhibit brittle breaking characteristics. However, for the finite element modeling of specimens with large braiding angle, the extended gradual unloading process observed in the computed stress-strain curves is considered as a numerical technique of displacement loading mode which can promote the numerical stability.

4.2 Prediction of fatigue life

In the fatigue analysis, the force loading mode is employed to predict the fatigue life and simulate the fatigue damage evolution of 3D braided composites subjected to fatigue tension loading. The prediction of *S*-*N* curve is the general objective of any fatigue experiment and simulation. According to the experiment results given by Qiu et al. [25], the *S*-log*N* curve of 2.5D textile composites under fatigue tension shows approximately linear relationship. In this investigation, the straight line is used to fit the prediction data points. Based on the predicted static strengths, different force loadings according to the determined stress levels are applied to the unit-cell models. The fatigue limit is set as 10^8 in the analysis while none of the predicted fatigue life reaches this value. The predicted *S*-log*N* curves of 3D braided composites specimens under tension-tension fatigue loading with stress ratio R=0.1 are presented in Fig. 4. It can be found that the fatigue life increases with decreasing the maximum fatigue stress level, and for specimen 2 with large braiding angle, the increase is more significant. Largely, the predicted *S*-log*N* curves of 3D braided composites here follow the similar tendency as those reported by Qiu et al. [25] for 2.5D woven composites.

4.3 Analysis of stiffness degeneration

The stiffness degradation process can reflect the extent of damage accumulation in the unit-cell model under fatigue loading. The residual stiffness here is defined by dividing the applied stress by the strain component in the loading direction. The stiffness degradation under different levels of fatigue loadings for two specimens is exhibited in Fig. 5. In this paper, the original number of cycles is set as 1. When the logarithm of number of cycles, log$n$, is smaller than 0, the stiffness curves express the stiffness variation under the initial static loading condition. In this stage, the slight decrease of the stiffness is due to the generation of some matrix cracks, as shown in Fig. 5(a). For specimen 1 with a small braiding angle, as the increase of log$n$, the stiffness degradation is not remarkable before the sudden decrease. On the contrast, as shown in Fig. 5(b), the stiffness degradation of specimen 2 with a large braiding angle decreases gradually until certain cycle where the sudden decrease happens. In the simulation, the sudden decrease of stiffness always indicates the final fatigue failure of composite specimen, which is resulted from the occurrence of extensive main damage modes. Overall, the degradation trends of stiffness with number of cycles of 3D braided composites presented here are consistent with those given in Ref. [23] for 2D woven composites.

4.4 Analysis of fatigue damage evolution

The advantage of the PFDM is that the complete fatigue damage initiation, propagation and final failure can be demonstrated under general fatigue loadings. In this paper, the fatigue damage evolution processes of 3D braided composites subjected to different tension-tension fatigue stress levels are simulated. The fatigue damage evolutions on the unit-cells of specimen 1 under 80% stress level and specimen 2 under 82.5% stress level are selected to analyze here, as illustrated in Fig. 6 and Fig. 7. It is observed that the stress concentration and fatigue damage initiation always happen in the yarn/yarn contact zones. Accordingly, in order to clearly display the damage distribution in the braiding yarns, only one-direction braiding yarns are presented here.

For specimen 1, the main fatigue failure modes are yarn L tensile fatigue failure and matrix cracking, which are similar to those under static loading. The numbers of T compressive shear and Z tensile shear fatigue failure elements in the braiding yarns are very limited. As shown in Fig. 6(a), L tensile fatigue failure starts in the braiding yarns when the number of cycles n is proximate to the fatigue life, and propagates quickly along the longitudinal and transverse directions of the yarn simultaneously. However, even when the fatigue life is reached, n=6.310e6, the number of damage elements with yarn *L* tensile fatigue failure is relatively small. Seen from Fig. 6(b), matrix cracking initiates before the fatigue analysis, that is, occurs in the static loading stage. It almost doesn't propagate until n=1.585e6, then spreads rapidly after yarn damage modes (especially yarn *L* tensile breaking) begin to happen because in this condition, resin matrix will bear greater amount of load. Consequently, yarn *L* tensile failure leads to the final tension fatigue failure of specimen 1.

For specimen 2, the main fatigue failure modes are yarn *T* compressive shear fatigue failure, yarn *Z* tensile shear fatigue failure, yarn *L* tensile fatigue failure and matrix cracking, which are some different to those under static loading. The occurrence of yarn *L* tensile fatigue failure mode can be attributed to the force loading condition in the fatigue analysis. As shown in Fig. 7(a), yarn *Z* tensile shear fatigue failure appears first in the yarn/yarn contact zones and propagates largely along the transverse direction of the braiding yarn. The propagation speed is slow and steady at the beginning and increases gradually with the increasing of number of cycles. *T* compressive shear failure of yarn is not given here since its expansion trend is basically the same as that of *Z* tensile shear failure except for the later appearance. Matrix cracking first appears in the intersecting edges of the braiding yarn and matrix and propagates rapidly in the intersection regions, resulting in lots of damaged elements, as shown in Fig. 7(b). When n is close to the fatigue life, yarn *L* tensile failure happens and propagates sharply until the final fatigue failure of composites, as shown in Fig. 7(c). Herein, since the fixed force loading is applied, the transverse failure of yarns and matrix cracking cause the braiding yarns to bear more additional axial load. The coupling and interaction of various failure modes lead to the final fatigue failure of specimen 2.

5 Conclusions

PFDM is one of the most useful and effective methods developed by researchers to study the fatigue behavior of composite structures under general fatigue loading conditions. In this paper, a CDM-based meso-scale finite element model is proposed to predict the fatigue life and analyze the damage mechanism of 3D braided composites under fatigue tension loading. The model is an integration of unit-cell structure, stress analysis, fatigue failure criteria and material property degradation scheme. Stress analysis is executed by finite element simulation based on a periodic unit-cell structural model. 3D Hashin failure criteria and maximum stress criteria are applied to detect the fatigue failure of braiding yarns and matrix respectively. Sudden stiffness degradation scheme is adopted to degrade the material property of elements triggered by fatigue failure criteria; stiffness and strength gradual degradation scheme is implemented to degrade the material property of elements due to fatigue cycles. This meso-scale modeling technique is carried out by using a user-material subroutine UMAT based on ABAQUS/Standard platform with FORTRAN code.

The progressive fatigue damage process is simulated and the damage mechanisms are analyzed. Moreover, the *S*-log*N* curves that determine the fatigue life of 3D braided composites are predicted and the stiffness degeneration processes under fatigue tension loading are also analyzed. It is found that the predicted *S*-log*N* curve of 3D braided composites under tension-tension fatigue loading shows approximately linear and the fatigue life increases with the decrease of stress level, and the increase is more significant for the specimen with large braiding angle. For the stiffness degradation, it is not notable before the sudden failure for the specimen with a small braiding angle, while it decreases gradually until certain cycle where the sudden failure happens for that with a larger braiding angle.

Since the PFDM is a general frame and the proposed meso-scale finite element model is generic in nature, it provides a suitable reference to the numerical study of the fatigue issues in other types of textile composites.

Although the experimental validation would be very helpful and interesting, no such experimental data for the fatigue mechanical behavior of 3D braided composites under considered loading cases is available in the literature. However, this work, on one hand, is the first complete numerical analysis to predict the fatigue properties of 3D braided composites, its obtained numerical results on the other hand would provide new data set for reference solutions using meso-scale FEA.

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