PROGRESSIVE FATIGUE DAMAGE MODELING OF TEXTILE COMPOSITE ON MESO-SCALE WITH FE-METHOD

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ABSTRACT

Aim of this work is to evaluate the tension-tension fatigue life and damage in textile reinforced composites on meso-scale level (fabric unit cell). Averaged stiffness, Poisson's Ratios in pre- and post material damage states are evaluated based on numerical homogenization technique with periodic boundary conditions (PBCs). Experimental S-N curves of unidirectional composites are utilized as input data for impregnated yarns which are taken as unidirectional composite. The outputs are calculated S-N curves, which show good agreement with experimental data.

1. INTRODUCTION

Fatigue design criteria of Textile reinforced composites are usually determined by experiments. However, due to the anisotropy and inhomogeneity of the material properties and the diverse architectures and design parameters of the reinforcement, considerable tests have to be performed and overestimated safe factors are applied. Thereby, a reliable numerical method for evaluation of the fatigue characteristics will be of great value.

Complete fatigue data for carbon fibre epoxy (AS4/3501-6) unidirectional composites was obtained by Shokrieh (ref.1). Those sets of experimental data are processed to produce the S-N curves used as input for the computational fatigue properties of textile composites. For validation, data of three plain weave/carbon fibre composites, published in (ref.2), is used. The computed strain-stress diagrams and S-N curves show good agreement with the experimental data.

2. FATIGUE MODELING

Modeling of fatigue damage is divided into three stages as defined in Fig.1(b): (A)Static loading is applied to intact unit cell. Loading increases gradually up to the magnitude of maximum fatigue loading $\sigma_{\max}$. The degraded properties are passed to fatigue analysis later. (B)During certain amount of load cycles, *N_jump* (ref.3), materials points have continuously experienced the weakening effects evaluated by Miner's rule. (C) After the stiffness deterioration of material points the FE-model will be unloaded and reloaded back to the maximum fatigue stress state – Fig.1(b). Consequence of the stress redistribution is the enlargement of damage zone.

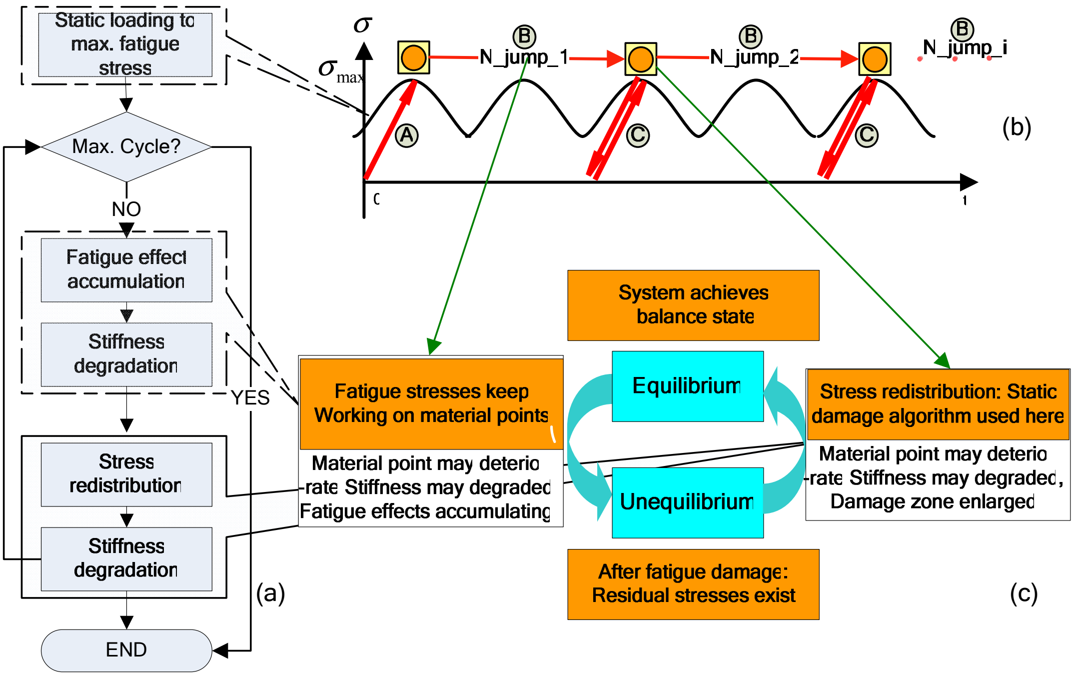


Fig.1 Sketch map of fatigue analysis of textile composites: (a) flow chart; (b)integration of static and fatigue algorithm; (c) residual stress release

2.1 Fatigue Damage Initiation Criterion in Yarns

2.1.1 Fibre Direction: Palmgren-Miner's Rule

The failure behavior and mechanisms of unidirectional composites in fibre direction are different from those of transverse fibre direction. The fibre breakage may be evaluated separately using directly Palmgren-Miner's rule – Eq.1. *Rs* is named as non-damaged fraction, which is ranged in between zero and one, with 'one' standing for intact material points and 'zero' for material points complete worn-out.

$$Rs_1 = 1 - D_1^j \quad , \quad D_1^j = \sum_{k=1}^{j} \frac{N^k_{\_jump}}{N_1^k(\sigma_1^k)} \tag{1}$$

Sub-index *1* indicates fibre direction. *j* is the current *N-jump* number. $N_1^k({}^k\sigma_1)$ is the cycle number capacity leading to failure according to the S-N curve of current stress level σ_I^k. The fraction *N-jump/N* is so-called damage fraction. D_I^j is the summation of all historical damage fractions.

2.1.2 Transverse Fibre Direction: Multi-axial Fatigue

Liu (ref.4) proposed a multi-axial fatigue model based on “critical plane”, a virtual plane on which hydrostatic stress effects may be neglectable. The “critical plane” depends on the “crack plane”, the physical micro-level fracture plane, and the materials properties. In his later paper (ref.5), Liu extended the model to unidirectional composite materials. Eq.2 is the condition for appearance of the matrix crack in the fibre bundle.

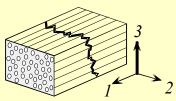
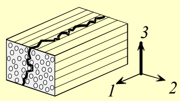
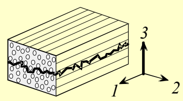
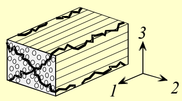
$$\frac{1}{\beta}\sqrt{\left[\sigma_{a,c}^2\left(1+\eta_N\frac{\sigma_{m,c}^2}{f(N,\theta_{crack})}\right)\right]^2+\left(\frac{f(N,\theta_{crack})}{t_{(I)}(N,\theta_{crack})}\right)\left(\tau_{a,c(I)}\right)^2+\left(\frac{f(N,\theta_{crack})}{t_{(O)}(N,\theta_{crack})}\right)\left(\tau_{a,c(O)}\right)^2+k\left(\sigma_{a,c}^H\right)^2}=f(N,\theta_{crack}) \quad (2)$$

In Eq.2, $\sigma_{a,c}$, $\sigma_{m,c}$, $\sigma_{a,c}^H$, $\tau_{a,c(\mathrm{I})}$ and $\tau_{a,c(\mathrm{O})}$ stand for normal stress, mean normal stress, hydrostatic stress, in-plane shear stress and out-of-plane-shear stress amplitudes on critical plane (subscript ‘c’). β and k depend on the ratio *s* of shear and tension fatigue limits, which are material properties related constants while α is the angle between crack plane and critical plane. These parameters are defined in (ref.4). Experimentally curve-fitted η_N describes the effect of mean normal stress. $f(N,\theta_{crack})$, $t_{(I)}(N,\theta_{crack})$ and $t_{(O)}(N,\theta_{crack})$ are fatigue strengths on crack plane at load cycle number *N*, which are tensile fatigue strength correspondent to the norm direction of crack plane, in-plane shear and out-of-plane-shear strength, respectively. θ_{crack} is the angle between the norm of crack plane and fibre direction.

2.2 Damage propagation and stiffness reduction Law

The fatigue damage initiation is captured by the multi-axial fatigue damage initiation criterion before fibre breakage (after fibre breakage, the material point is considered to be completely damaged). A material point post-damage behavior for both static and fatigue loading is described by an anisotropic damage mode -- Table 1. Numbers *1*, *2* and *3* correspond to longitudinal, transversal and vertical direction to fibre bundles, respectively. *t* and *c* stand for the tension and compression. Mode *1* corresponds to fibre breakage while other modes to inter-fibre cracks. The post-damage stiffness matrix will be computed based on the damage tensor of the damage mode. The damage mode is identified by the maximum value of the stress-to-strength ratios (ref.6-7), shown in Table 1.

Table 1. Anisotropic damage mode

Damage mode	Anisotropic damage model for fiber				Isotropi damage model for matrix
	Mode 1 	*Mode 2 & 12* 	*Mode 3 & 13* 	*Mode 23* 	
Maximum stress-to-strength ratio	$\frac{\sigma_1^{\ 2}}{S_1^t\ S_1^c}$	$\frac{\sigma_2^{\ 2}}{S_2^{\ t} S_2^{\ c}}$ or $\left(\frac{\tau_{12}}{S_{12}}\right)^2$	$\frac{\sigma_3^{\ 2}}{S_3^{\ t} S_3^{\ c}}$ or $\left(\frac{\tau_{13}}{S_{13}}\right)^2$	$\left(\frac{\tau_{23}}{S_{23}}\right)^2$	——
Damage tensor $\begin{bmatrix} D_1 & 0 & 0 \\ 0 & D_2 & 0 \\ 0 & 0 & D_3 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

Di is the principle value. Damage factor D_i stands for effective area reduction caused by voids and cracks (ref.7) while $D_i = 0$ means intact material point and $D_i = 1$ for complete damaged material point.

Two frames concern fibre breakage and transverse-fibre cracking. Fibre breakage predominates the fatigue damage. Once fibres fail, the program will move on to evaluate the next Gaussian point. Otherwise, the program goes to transverse-fibre cracking evaluation by Eq.2 to determine the fracture plane angle which links to the corresponding damage modes in Table 1 by means of crack angle θ_{crack} .

3. VALIDATION OF THE FATIGUE MODEL

3.1 Materials

Experimental data (ref.2) of three types of textile reinforced carbon fibre epoxy composites, plain weave 12K (PW12K), plain weave 3K (PW3K) and spread-tow plain weave 12K (ST12K), are utilized to validate the model. They are provided with the same resin system, the same intrinsic properties, but different design parameters.

Table 2. Reinforcement for three plain weave carbon/epoxy composites

Characteristics		**(Vf=50.4%)**	
No. of fibres in tow	**12K**	**3K**	**12K**
Tow width(mm)	**20**	**2**	**4**
Tow thickness (mm)	**0.05**	**0.075**	**0.15**
Crimp angle (º)	**1**	**5**	**10**
Specimen name	**ST12K CFRP**	**PW3K CFRP**	**PW12K CFRP**

Table 2 lists the physical properties of the unit cells for the three materials. The new type of plain weave has the largest unit cell size, smallest thickness and the smallest crimp angle. The unit cell geometry is recovered by WiseTex.

3.2 Input Data for Yarns

Yarns are represented as impregnated UD composite. Stiffness matrix components, Poisson's ratios and strengths are calculated through experiential equations(ref.6). Additionally, fatigue model requires S-N curves of unidirectional composite, for loading in fibre/transversal fibre/in-plane-shear/out-of-plane-shear direction, shown in Fig.2, extracted from (ref.1). In fibre direction, the so-called Semi-Logarithmic-Bilinear model (ref.8) --Eq.3 is used as regression representation of S-N curves.

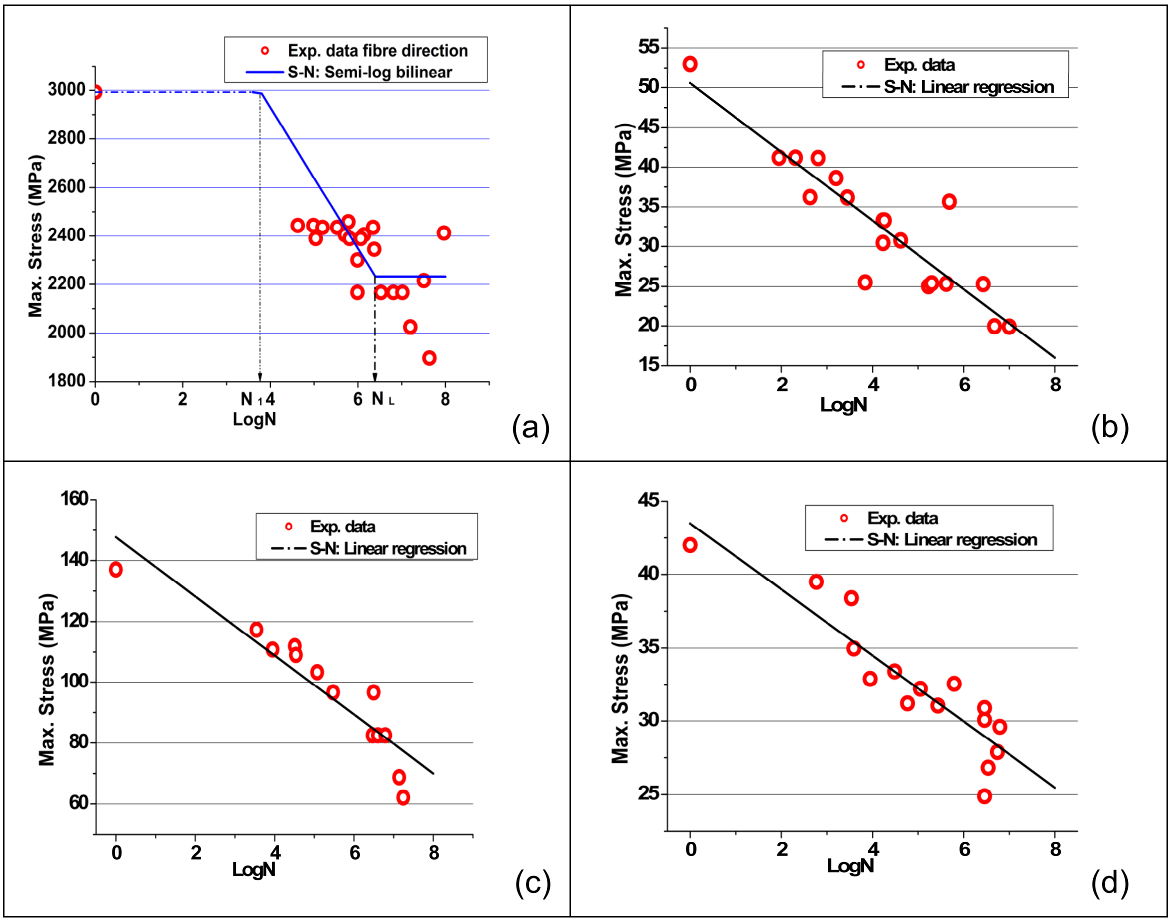


Fig.2 UD data as Input: (a) fibre tension-tension; (b) transverse fibre tension-tension; (c) in-plane shear; (d) out-of-plane shear

$$\begin{cases} S = S_{static} & N \le N_I \\ S = -A\log_{10}N + B & N_I < N \le N_L \\ S = E & N > N_L \end{cases} \quad (3)$$

S and *N* stand for fatigue strength and cyclic loading number respectively. *A*, *B*, are constant coefficients evaluated by regression method, *E* is the fatigue limit. N_I is the point where strength starts decreasing for calculation and N_L is the number of load cycle, at which the sample reaches fatigue limit.

3.4 Validation

Good agreement between the modeling and experiments are obtained, especially at the prediction of the tendency of fatigue properties, fatigue strengths for instance, improvements due to the design factors of the preform architecture. The composite with spread tows gives the highest fatigue strength approaching that of unidirectional composite as an utmost – Fig.3.

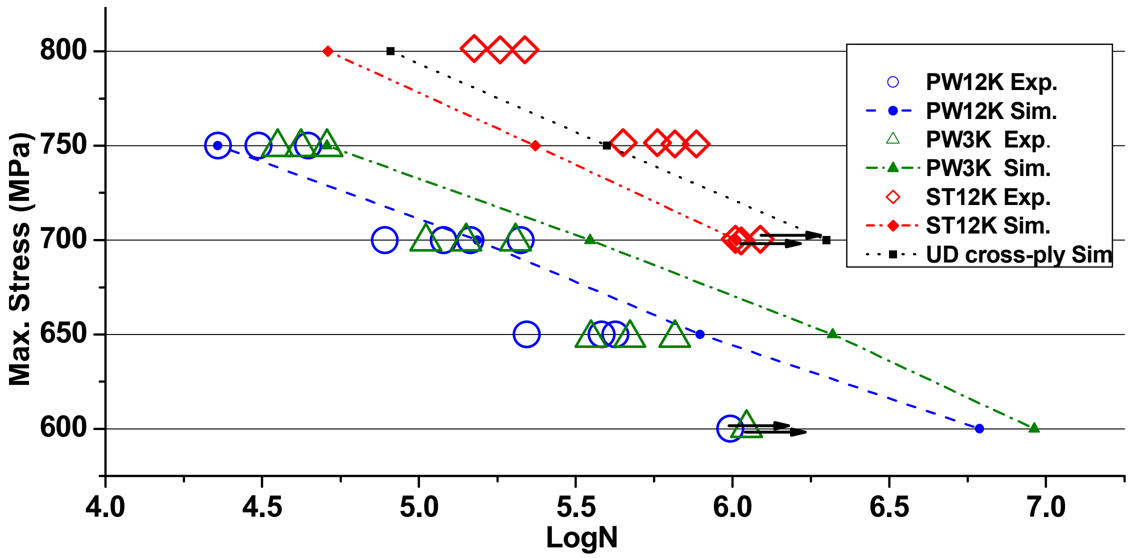


Fig.3 Experimental and computed S-N curves for plain weaves and UD

4. CONCLUSIONS

A promising numerical procedure for prediction of fatigue damage initiation and evolution in the unit cell of textile composites under the tension-tension fatigue loading is developed. The dedication of this model is able to prognosticate the trend of the fatigue properties betterments, strength reduction curves for instance, versus improved design parameters. The program provides details and possibility to gain an insight to the local stresses and strain distribution along the fatigue life, meaningful for the optimization of textile composite architecture.

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