Tension-compression fatigue behavior of 3D woven composites

Yao Siyuan and Chen Xiuhua

School of Aeronautics and Astronautics, Shanghai Jiao Tong University, 800 Dongchuan Road, 2100240, Shanghai, P.R.China

E-mail: chenxiuhua@sjtu.edu.cn

Abstract. In order to investigate the fatigue behavior of three-dimensional (3D) woven composites under tension-compression cyclic loading, fatigue tests which had a stress ratio of R=-1 were conducted. Under different loading levels, weft and warp fatigue tests were conducted. The hysteresis loops and curves of residual stiffness ratio via fatigue life were obtained. It is implicated that the fatigued damage progress of 3D woven composites under tension-compression cyclic loading contains three stages mainly, in which the failure of matrix, transverse crack propagation inside the yarns and the fracture of yarns occur in sequence. The crush and debonding of matrix, the avulsion of yarns which are perpendicular to the loading direction and the fracture of yarn which are along the loading direction are major failure modes. Semi-empirical models are obtained to describe the fatigue process and forecast the fatigue life of 3D woven composites. The mathematical equations fit the experimental results well.

1. Introduction

3D woven composites are currently being used as a class of aerospace material which combine lightweight with high damage tolerance. The high damage resistance of 3D woven composites is derived from through-thickness structural fibers, which resist large-scale delamination crack growth [1]. These enhancements motivate much of the present research on the mechanical properties of 3D woven composites.

Jin L et al [2] investigated the three-point bending fatigue damage behavior of 3D angle-interlock woven composites. The resin cracks, the yarns cracks and the resin-yarns interface debonding are the three modes of fatigue damage for the 3D woven composites. Dai S et al [3] presents a study on the open-hole quasi-static tensile and tension-tension fatigue behavior of an orthogonal and an angle-interlock 3D woven composites. The residual fatigue strength was found to be similar to the quasi-static tensile strength in both weaves. The surface crack initiation and progression during fatigue loading was identified using thermoelastic stress analysis which revealed that the orthogonal weave had larger surface damage area than the angle-interlock weave. Yu B et al [4] conducted a detailed investigation of failure mechanisms for angle-interlocked (AI) and modified layer-to-layer (MLL) 3D woven composites under tension-tension fatigue loading using surface optical microscopy, cross-sectional SEM imaging, and non-destructive X-ray computed tomography. A higher crack density was found in the AI composite than the MLL composite. Transverse cracking initiates in the fiber rich regions of weft yarns rather than the resin rich regions. Delamination in the failed MLL specimen were more extensive than the AI specimen. Using time-lapse X-ray computed tomography (CT), Yu B et al [5] also found the fatigue damage of 3D woven composites distributed regularly throughout the

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composite according to the repeating unit, even at large fractions of the total life. Roirand Q et al [6] modelled the failure mechanisms of 3D woven composites on 3D periodic cells by finite element calculations. A stochastic approach was applied to a simple representative elementary periodic cell. It was shown that this stochastic approach allowed more realistic failure simulations avoiding the idealized symmetry due to the deterministic modelling. Wilkinson M P and Ruggles-Wrenn M B [7] studied the tension-tension fatigue behavior of two polymer matrix composites (PMCs) at elevated temperature, which are the non-crimp 3D orthogonal weave composite (3D PMC) and the laminated composite (2D PMC). The 3D PMC offered improved delamination resistance.

Previous studies on fatigue properties of 3D woven composite materials mainly focus on three point bending fatigue and tension-tension fatigue. In order to investigate the tension-compression fatigue behavior of 3D woven composites, both weft tension-compression fatigue tests (WETCF) and warp tensions-compression fatigue tests (WATCF) were conducted. The fatigue damage was described based on the experimental phenomenon and results. Semi-empirical models are obtained to describe the fatigue process and forecast the fatigue life of 3D woven composites. The experimental results verified the validity of the models.

2. Experimental

2.1. Material

The unit cell of the material is shown in figure. 1, consisting of weft, warp and binder carbon fiber yarns and resin matrix. Each periodical unit cell contains four bundles of weft yarns in the direction of length. One binder yarn spans three weft yarns, weaving two layers of weft yarns together. The warp layer is located between the two layers of weft yarns and is arranged with binder yarns. The thickness of a specimen is determined by the number of layers. The specimens used in the fatigue tests contains 7 layers of weft yarns and 6 layers of warp yarns.

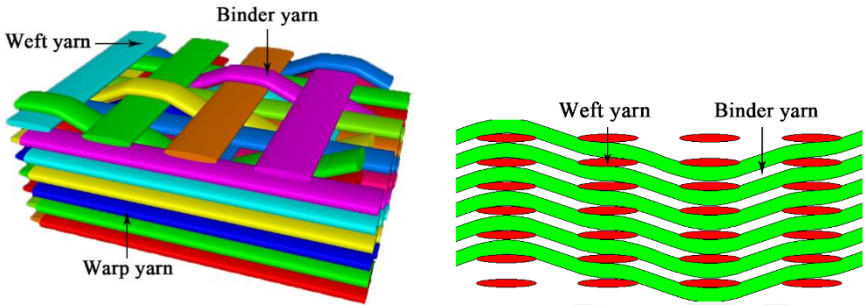


Figure 1. Unit cell structure of the fatigue test specimen.

The tension and compression strength values of the material are shown in table 1, which are obtained from static tests.

Table 1. Ultimate strength of 3D woven composites.

Load Direction	Tension strength/MPa	Compression strength/MPa
Weft	687	370
Warp	855	487

2.2. Tension-compression fatigue tests

Fatigue tests along weft and warp direction which had a stress ratio of R=-1 were conducted. Both weft and warp fatigue tests contain four specimens under different stress level. The stress level of tension-compression fatigue tests is defined as the percentage of peak stress over compression strength. The arrangement of stress level is shown in table 2.

Table 2. Stress level arrangement of fatigue tests.

Direction	Stress level/%			
Weft	47.7	39.8	31.8	23.9
Warp	48.3	42.3	36.2	30.2

The equipment and installation are shown in figure 2. The test machine recorded the number of cyclic loading, the loading force and the displacement of hydraulic chuck. the extension meter records the shape variables that occur during the test process.All tests are conducted under load control, of which the loading frequency is 15 Hz. The tests are completed when the fracture of specimen occurs or the specimen cannot carry the test load.

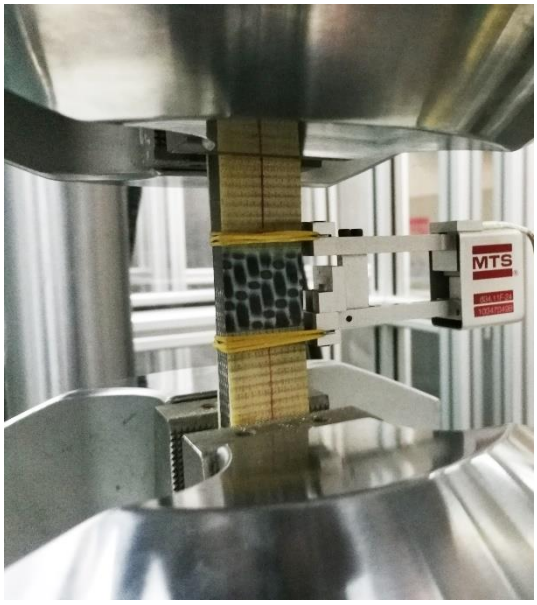


Figure 2. Apparatus and installation fatigue tests

3. Results and discussions

3.1. Fatigue fracture analysis

Table 3 shows the fatigue life of tension-compression fatigue specimen for 3D woven composites.

Table 3. Fatigue life a of tension-compression fatigue specimen.

WETCF			WATCF		
No.	Stress level/%	Fatigue life	No.	Stress level/%	Fatigue life
S1	47.7	11048	S1	48.3	46155
S2	39.8	132672	S2	42.3	100008
S3	31.8	895942	S3	36.2	481172
S4	23.9	7133147	S4	30.2	2173790

The failure region of specimens are observed under an optical microscope, as shown in figure 3. The crush and debonding of matrix, the avulsion of warp yarns and weft yarns and the fracture of weft yarns are major failure modes of weft tension-compression fatigue specimens. The fracture is nearly neat because of the flat shape of weft yarns. The cross sections of warp and binder yarns are all distorted and cracks distribute on the surface randomly. Specimens under high stress level tend to appear large distortion of warp and binder yarns, while the surface of specimens under low stress level

show more fracture of weft yarns and matrix failure.

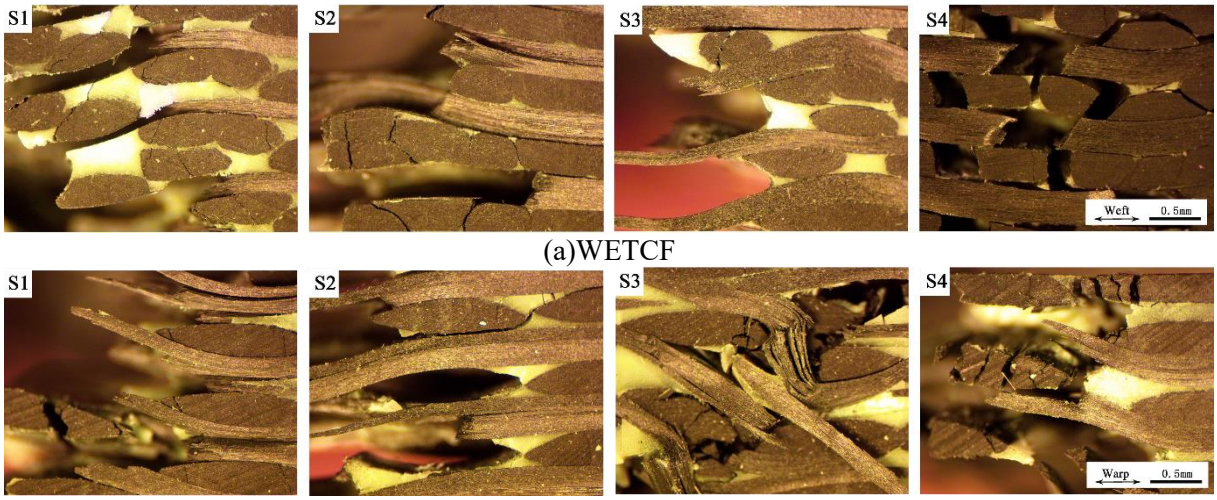


Figure 3. Micro pictures of the fracture region.

For warp tension-compression fatigue tests, the cross sections of warp yarns are round and thick, which makes it a longer period of crack propagation. At the end of crack propagation, the remaining warp yarns are not enough to bear the load. Thus irregular breakage and separation of yarns will occur. Kink and avulsion of binder yarns can be observed because of compression load and the concentrated stress given by weft yarns. Specimen under low cyclic load accumulates many crack propagation path. The weft yarn in the fracture path is eventually perforated by multiple cracks.

3.2. Stiffness reduction mechanism

Curves of residual stiffness ratio via normalized fatigue life are obtained, in which the residual stiffness ratio is defined by residual structure stiffness over initial structure stiffness. As shown in figure 4, it is implicated that the fatigued damage progress of 3D woven composites under tension-compression cyclic loading contains three stages mainly, in which the failure of matrix, transverse crack propagation inside the yarns and the fracture of yarns occur in sequence.

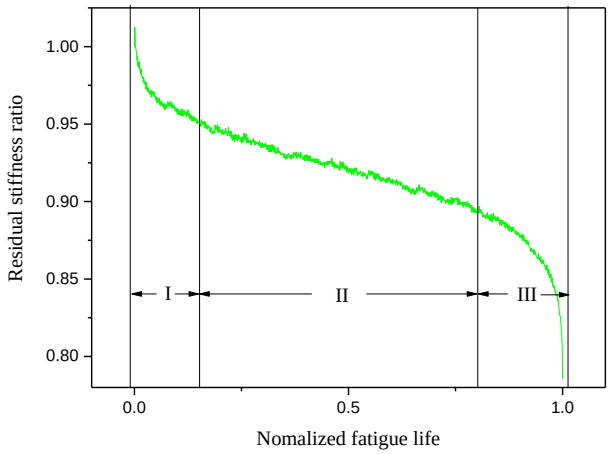


Figure 4. The three stages of tension-compression fatigue damage process.

Figure 5 shows all the specimen's curves of residual stiffness ratio via normalized fatigue life.

Higher stress level results in a longer period of stage II, while lower stress level causes longer stage I and III. Under lower stress amplitude, the strain of matrix is smaller. Thus it is slower for matrix to become failure, which means a longer period of stage I. In the meantime, lower stress makes the fracture of fiber yarns more stochastic instead of deterministic, so stage III tends to be a longer period.

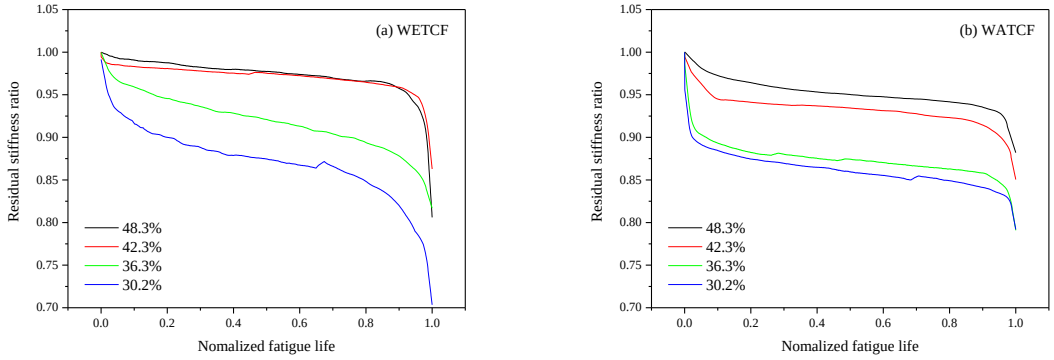


Figure 5. Residual stiffness ratio of tension-compression fatigue specimens.

3.3. Semi-empirical model

A semi-empirical models is investigated to fulfil the needs of engineering and design, as presented in Eq. (1).

$$\frac{E}{E_0}=1-\left(1-\frac{E_f}{E_0}\right)\left[q\left(\frac{n}{N_f}\right)^{m_1}+(1-q)\left(\frac{n}{N_f}\right)^{m_2}\right] \tag{1}$$

where E is the elastic modulus of the material during fatigue tests and E_0 is the elastic modulus of the material before the fatigue tests. E_f is the final modulus of the specimen when the test is completed. In reality, it would probably be zero or a value which is determined by the engineering practice. n is a certain cycle during the fatigue test and N_f is the final fatigue life. In addition, q, m_1 and m_2 are constants determined by the type of material and loading. These constants can be obtained through the least squares fitting method. Eq. (1) is similar to the equation in reference [8].

The mathematical equation describes the relation between the residual stiffness ration and normalized fatigue life. It can be applied to predicate the fatigue life of a serving 3D woven composite structure under tension-compression cyclic load, of which the stress ratio is R=-1. Table 3 shows the parameters of WETCF and WATCF under certain stress level.

Table 4. Fitting parameters of the semi-empirical model.

WETCF				WATCF			
No.	m_1	m_2	q	No.	m_1	m_2	q
S1	0.221445	342.7864	0.268961	S1	0.317528	21.0989	0.422061
S2	0.405357	118.5152	0.386728	S2	1.139266	138.5319	0.374316
S3	0.213681	36.32672	0.172382	S3	0.428574	66.56646	0.222634
S4	0.14014	120.9351	0.634219	S4	0.897774	123.3586	0.155348

Now that the parameters of WETCF under the stress level 31.8% have been obtained, fatigue life can be predicted for specimen under the same stress level. Another two WETCF specimen, S3-1 and S3-2, were tested under the stress level 31.8%, of which the fatigue life are 701931 and 471422,

separately. Based on the experimental data, the E/E_0 of S3-1 at cycle 200000 is 0.937348 and that of S3-2 is 0.934345. Given E_f = 0.5, thus the calculated fatigue lives are 890868 and 715819. The errors are 26.9% and 51.8%, which are acceptable.

4. Conclusions

The following conclusions can be drawn from the study.

1) The fracture of fibers, the avulsion and kink of yarns and the crush and debonding of matrix are major failure modes of tension-compression fatigue specimens.
2) The fatigue damage progress of 3D woven composites under tension-compression cyclic loading contains three stages mainly. During stage I, the stiffness of specimen declines rapidly and then slows down before stage II, which is dominated by matrix failure. During stage II, yarn cracks propagate perpendicular to the loading direction, causing the steady decline of structure stiffness. The fracture of yarns occurs during stage III, which results in the sharp decline of the stiffness.
3) Stress level effects a lot on the fatigue process of 3D woven composites under tension-compression fatigue. Higher stress level results in a longer period of stage II and lower stress level results in longer periods of stage I and III.
4) Semi-empirical models are obtained to describe the fatigue process and forecast the fatigue life of 3D woven composites. The mathematical equations fit the experimental results well.

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