Composite Structures 136 (2016) 64–74

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Investigation on tension–tension fatigue performances and reliability fatigue life of T700/MTM46 composite laminates

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ARTICLE INFO

Article history:
Available online 9 October 2015

Keywords:
Carbon fiber reinforced polymer
Tension–tension fatigue
Distribution test
Single side allowance factor
Reliability fatigue life

ABSTRACT

Tension–tension fatigue performances of T700/MTM46 composite laminates were investigated in this paper and the fatigue limit was determined. Failure modes of the fatigue specimens are mainly characterized by severe delamination throughout the whole gauge length while the static tension specimens exhibit brittle fractures within a small region. The stiffness degradation shows a quasi-linear slow decline during approximately 0–80% fatigue life and has a sharp decline since 80% fatigue life. Damage evolution was studied by fatigue specimens' edge view, which showed the damage in 90° plies initiate firstly and propagate most seriously during fatigue. The distribution of fatigue life was determined. Single side allowance factor was proposed to calculate the reliability fatigue life with both reliability and confidence level. The results show that reliability fatigue life reduces more when the reliability increases than when confidence level does to the same degree. A new fatigue model (p–γ–S–N curve) was also established to predict the reliability fatigue life.

1. Introduction

Carbon fiber reinforced polymer (CFRP) composites are widely used for primary load-bearing structures in aeronautics engineering [1]. They exhibit higher strength-to-weight, stiffness-to-weight ratios and good fatigue resistance, thus making the aircraft lighter and improving performance [2–5]. The CFRPs are becoming more and more popular to be an excellent replacement for traditional metallic materials [6,7]. Although good fatigue resistance is shown, the fatigue performances of CFRP composites are still investigated by many researchers because of their long service life (usually more than 30 years) for both military and civil aircrafts [8–23]. In many previous studies, the residual strength was often used to evaluate the damage of CFRP composites under fatigue condition [8–13]. Usually residual strength decreases as the number of fatigue cycles increases because of damage such matric cracks and delamination which results from fatigue load [8–12]. However, some researchers also found the opposite results that the residual strength increases after a certain number of fatigue cycles. The reasons for the rise of residual strength are that much off-axis fibers have been reassigned to the loading direction under fatigue condition [13]. This method was limited because the specimens had to rupture to get the residual strength, which is often unacceptable because of the high cost. Thus many non-destructive evaluation (NDE) techniques were later developed to evaluate the damage of CFRP composites under fatigue, such as infrared thermographic techniques [14], acoustic emission [15], X-ray radiography [16] and X-ray micro-computed tomography (μCT) [17]. Using these NDE techniques, many non-destructive parameters such as temperature, crack density and delamination, which could present the damage of CFRP composites were measured and investigated without destroying the specimen. Tate and Kelkar [18] and studied the stiffness degradation of CFRP composites and observed that there were three stages in stiffness degradation. The stiffness decreased rapidly at the beginning (approx. 0–15% fatigue life) and ending (approx. 85–100% fatigue life) of fatigue life. On the contrary, it tends to decrease relatively slowly in the middle fatigue life (approximately from 15% to 85% fatigue life). Additionally, a stiffness degradation model was proposed and it can reach a good agreement in experimental results. Montesano and Chandra [19] established a multiscale model based on synergistic damage mechanics. This model is powerful to predict the elastic response of symmetric composite laminates containing matrix cracks in plies of multiple orientations, and subjected to an arbitrary multiaxial strain state. The proposed multiscale model invokes 3D finite element analysis to characterize the multiaxial damage state within the cracked multidirectional laminate. Additionally, this approach is effective to evaluate

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http://dx.doi.org/10.1016/j.compstruct.2015.09.057
0263-8223/

damage constants required in the damage constitutive model, which can capture the ply constraint effects acting on the surface displacements of the matrix cracks in all off-axis and on-axis plies. Montesano et al. [20] investigated the fatigue strength and damage progression of 5 and 8 harness satin woven carbon fiber/epoxy composites subjected to in-plane tensile and fatigue loading using infrared thermography. Few previous studies have focused this issue. The relation between temperature profiles and stiffness degradation was clearly affirmed. Montesano Chandra [21] also developed an energy-based model to predict the evolution of sub-critical matrix crack density in symmetric multidirectional composite laminates for the case of multiaxial loading. The proposed model utilized computational micro mechanics to define ply level matrix crack critical strain energy release rates and the laminate material damage constants, which is more advantage when compared to the current existing models reported in previous literature. Rosa and Risitano [22] determined the fatigue limit based on the stabilization of rising temperature for CFRP composites under various stress level. The new proposed stiffness degradation model can well describe the experimental results. Arief et al. [23] studied the relationship between the crack density and fatigue stress for various stitch density carbon/epoxy composites. This research is concerning the effect of stich density on the fatigue performance early. Undoubtedly, the damage of CFRP composites is complex, which incorporates many types of damage such as intra-ply delamination (delamination within plies), inter-ply delamination (delamination between plies), transverse cracks, oblique cracks, fiber breakage, interface debonding and so on. However, how and where the damage initiates and evolves is still not fully understand and need further investigation.

For many conventional metallic materials, the fatigue life data usually obeys to log-normal distribution [24] or Weibull distribution [25,26] and shows a relatively small dispersion. However, the failure of CFRP composites under fatigue which includes a combination of various types of damage is far more complex than traditional metallic materials [27,28]. There can be a large dispersion in fatigue life data due to the complexity of failure coupled with inevitable defects generated in manufacturing process. The dispersion may vary among two orders of magnitude or even more at the same given stress level [29–31]. The large dispersion of fatigue life data may trigger many difficulties and cause confusion for aircraft designers to acknowledge the fatigue performances and reliability of CFRP composites which play important roles in ensuring the safety of aircrafts. Therefore, it is imperative to explore the distribution and reliability of fatigue life data. Some previous researchers have already focused on this problem. Chiachio et al. [32] conducted a review of current developments of the reliability in composites and described their influence on the design and optimization of composites. The lack of studying in reliability fatigue life of composites was highlighted in this paper. Raman and Rakesh [33] studied the rotating bending fatigue of glass-fiber reinforced polymeric composites. Two parameter Weibull distribution was applied to describe the *S*–*N* relationship at various failure probabilities P_f ($P_r = 1 - P_f$, where P_r is the survival probability), but this study failed to incorporate the confidence level to graph the *S*–*N* curve. Raif and Irfan [34] graphed the *S*–*N* curve of glass-fiber reinforced polyester composites with different reliability by using two parameter Weibull distribution. Unfortunately, the confidence level was also excluded in the *S*–*N* curve. Other researchers [35–37] also predicted the reliability fatigue life of various composites using different distributions. However, all of them failed to predict the reliability fatigue life incorporating both the reliability and confidence level.

In this paper, static tension and tension–tension fatigue experiments were conducted to investigate the fatigue performances of T700/MTM46 composite laminates. Both the log-normal and three parameter (3P) Weibull distribution were applied to describe the fatigue life distribution and a better one was chosen to study the reliability fatigue life. An approach incorporating both reliability and confidence level to evaluate the reliability fatigue life was proposed.

2. Experimental

2.1. Materials

The specimens used were carbon/epoxy resin composite laminates, which were made of UD prepreg T700/MTM46. The materials were cured at 70 °C for 90 min and post-cured at 135 °C for 60 min in an autoclave facility. The material properties of T700/MTM46 are shown in Table 1, which are provided by the manufacturer, AVIC Beijing Institute of Aeronautics Materials. Plies sequence of the laminates was [45/90/−45/0/45/0/−45/90/0]s. The nominal dimensions of laminates were 250 mm × 25 mm × 2.4 mm (length × width × thickness). All specimens were end tabbed with 2 mm thickness glass fiber reinforced polymer end-tabs, leaving a gauge length of 150 mm.

2.2. Experimental methodology

Static tension experiments including total three specimens were conducted to determine the ultimate tensile strength (UTS) according to ASTM D3039/D3039M [38] on MTS 810 servo-hydraulic test machine (MTS Systems Co. USA) under displacement controlled method, with displacement rate of 1 mm/min. Tensile strain was measured using an extensometer with 50 mm gage length fixed on the gauge-length section of specimen.

Tension–tension fatigue experiments were conducted under a constant amplitude load controlled method according to ASTM D3479/D3479M [39]. Basic fatigue experiment parameters were sinusoidal waveform at 10 Hz frequency and a stress ratio of $R = 0.1$. The fatigue stress levels (σ_{max}) were applied as percentage of the UTS obtained from the static tension experiments, starting from 65% up to 90% of average UTS in steps of 5%. At each stress level, a total five specimens were studied. The fatigue experiments were interrupted if the specimens survived over 10^6 cycles. The max-fatigue load under which specimens can survive 10^6 cycles is defined as fatigue limit in this paper. The experimental setups are shown in Fig. 1.

3. Experiment results and discussion

3.1. Static tension experiment

The stress–strain curves of T700/MTM46 laminates are shown in Fig. 2. The curves of all three specimens have a good linear property and are quite repeatable. For lots of fiber reinforced composites laminates with a relatively large proportion of 0° plies, its stress–strain behavior can exhibit a total linear property throughout the whole loading history [40]. The UTS, modules and ultimate strain are listed in Table 2. Average UTS, modules and ultimate strain are 840.6 Mpa, 49.2 Gpa and 0.01710 with coefficient

Table 1
Material properties of T700/MTM46 (in MPa).

E_{11}	E_{22}	E_{33}	G_{12}	G_{13}
124,130	8800	8800	4470	4470
G_{23}	υ_{12}	υ_{13}	υ_{23}	
3260	0.328	0.45	0.328	