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Effect of ply-drop on fatigue life of a carbon fiber composite under a fighter aircraft spectrum load sequence

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ABSTRACT

Carbon fiber composite laminate containing symmetric internal ply-drop simulating thickness variation was fabricated and tested to determine fatigue life under a standard mini-FALSTAFF spectrum load sequence. The fatigue life of ply-drop composite was significantly lower than that of plain composite due mainly to initiation and growth of delamination near the ply-drop location. The spectrum fatigue life was also predicted by empirical method. For this purpose, static and constant amplitude fatigue data was generated to construct constant life diagrams (CLDs). The spectrum fatigue life predicted using CLDs was in good agreement with experimental results for both plain and ply-drop composites.

1. Introduction

Fiber reinforced polymer (FRP) composites are extensively used in construction of primary aircraft structural components. Recent airframes are built with as high as 50% of FRPs. The high specific strength, stiffness and tailorability of composites make them very attractive materials for airframe applications. The laminated structural FRP composites generally consist of continuous carbon fibers reinforced in a thermosetting epoxy matrix. Each of the lamina is laid up in a specific orientation to produce multidirectional laminates of required strength and stiffness. Due to design requirements, the thickness of composite needs to be varied from place to place within a single component such as in the wing of an airframe. Such thickness variations in composites are incorporated by use of ply-drops. There are several basic types of thickness variations induced in laminated composites through ply-drop construction and can be broadly classified as [1] external, internal and mid-plane ply-drop constructions.

The structural components experience several types of static and fatigue loads in service. Being a stress concentration location, presence of ply-drop in the component could be detrimental to the strength and durability of the structure. Several studies have shown that stress concentration due to ply-drop reduce the static strength of composites. Vidyashankar et al. [2] estimated the tensile strength of a tapered laminate with ply-drop and identified the presence of high stress concentration and occurrence of local bending. They also brought out the susceptibility of ply-drop zones to the onset and growth of delamination. Similarly, Steeves and Fleck [3] observed that delamination initiate near the ply-drop leading to failure and result in reduction of compressive strength of a tapered laminates. Thomsen et al. [4] showed that delamination initiates at ply-drop due to local bending effects in the tapered face sheet of sandwich under tensile loads. Winsom et al. [5] showed that delamination near the ply-drop could be suppressed by chamfering. Xing et al. [6] studied failure mechanism of laminates with internally dropped plies and showed three basic failure modes for different interply strengths under tension and compression loading. Andrews et al. [7] investigated the delamination behavior in composites with flat sheet geometry having thickness variation and observed that boundary and loading conditions influence significantly. Cui et al. [8] predicted the static

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strength of tapered laminates satisfactorily using variable fracture energy model. Winsom et al. [9] studied the behavior of delamination in asymmetrically tapered composites subjected to tensile loads.

Many studies on FRP laminates have shown that the presence of ply-drop reduces the fatigue strength of composite significantly. Fatigue damage initiation and growth according to Cairns et al. [10] is strongly sensitive to ply-drop location and manufacturing details. They observed that it is difficult to completely suppress damage and delamination initiation at ply-drop. Helmy and Hoa [11] observed that fatigue crack initiates at the resin pocket near ply-drop and propagates along the interface under mode II conditions. They showed that addition of nanoclay in the epoxy enhance the fatigue life by reducing speed of growth of delamination. Giannis [12] used fracture mechanics parameters to estimate the fatigue performance of FRP tapered laminates. He observed that onset of delamination and growth at ply-drop could be accurately evaluated using strain energy release rate. Murri and Schaff [13] observed that nonlinear-tapered flex beam specimens under combined constant axial tension and cyclic bending loads failed by delamination in the tapered region. They also observed that the initial delamination growth from the tip of the ply-drop toward the thick region of the flex beam was of mode II type.

Compressive fatigue failure of composites containing ply-drop was investigated by Wang et al. [14] who observed that specimens with longitudinal discontinuous plies did not fail in compression but rather failed by delamination initiating at ply-drop. Also, they observed similar failure mechanisms under both static and fatigue loads. Weiss et al. [15] investigated the influence of ply-drop position in thickness direction under completely reversed fatigue loads. They identified that first damage clearly is delamination close to the ply-drop. Stress concentration due to ply-drop leading to initiation of delamination and its growth has been observed in tapered composites by several investigators [10,14,15]. Helmy et al. [11] observed that fatigue crack initiates at the resin pocket near ply-drop and propagates along the interface under mode II conditions. Delamination has been observed to initiate due to interlaminar stresses resulting from ply-drops [11].

Finite element modeling and stress analysis of ply-drop in composites has been carried out by several investigators [1,16–19]. Her [16] used a combination of analytical and numerical method to analyze the ply drop-off problem. Dhurvey and Mittal [20] recently reviewed the analysis efforts made on tapered laminates with respect to static and dynamics analysis, buckling analysis, vibration analysis, delamination and interlaminar stress analysis. He et al. [21] developed a modified shear-lag model and analyzed the UD laminate with ply-drop subjected to tensile loads. Stress analysis of laminates with internal ply-drop has been carried out by Kim et al. [22] and stacking sequence table was used by Irisarri et al. [23] to design composites containing ply-drops. Design consideration for composites with ply-drop has also been studied by several other investigator [24,25].

Most of the fatigue studies on laminates with ply-drop or tapered laminates are limited to constant amplitude fatigue loads. Very few studies have been made on the ply-drop laminates under spectrum fatigue simulating service loads. Meirinhos et al. [26] showed that the stress amplitude of the civil-aircraft fatigue spectrum did not create any damage in the tapered section and has no contribution to the propagation of delamination when maximum 20° tapered specimens are used. The main aim of this work was to study the effect of symmetric ply-drop on the fatigue life of composite under a standard fighter aircraft spectrum load sequence. Also, an attempt was made to predict the fatigue life under the spectrum load sequence using empirical method and compare with experimental results.

2. Experiments

2.1. Material

Unidirectional T300 carbon fabric and thermosetting epoxy RTM120 were obtained from M/s Hexcel used to fabricate two types of laminates by resin transfer molding technique, VERITy process [27] Viz., (i) plain laminate (termed as PLL composite) with a lay-up sequence of $[+45/-45/+45/0/-45/90]_s$ and (ii) ply-drop laminate (termed as PLD composite) with a lay-up sequence of $[+45/-45/0/90/+45/0/90/+45/-45/0/90]_s$. The PLD was a symmetric and internal type of ply-drop construction [1] to induce thickness change from about 2.04 mm to about 3.74 mm over a length of 25 mm with a taper angle of about 2° as shown in Fig. 1. The laminates fabricated had a fiber volume fraction of 0.6.

2.2. Static mechanical properties

The static tests were conducted to determine the tensile and compressive strength of the material. The mechanical properties were determined following their respective ASTM test standard specifications [28,29]. All the static tests were performed in a 100 kN computer controlled servo-hydraulic test machine with a constant crosshead speed of 1 mm/min. Three replicate tests were conducted and the average properties were determined as shown in Table 1. The stresses were calculated in the thin section of the ply-drop composite [3]. The presence of ply-drop reduced both the tensile and compressive strength of composite. Similar observation has been made by several others [3,30]. Curry et al. [30] explained this reduction on the basis of axial stiffness difference between thin and thick sections of the laminate. The tensile and compressive strength data was used for construction of constant life diagrams (CLDs) as explained later.

2.3. Fatigue testing

Fatigue tests on composites were conducted under a standard spectrum load sequence. The load sequence used was a fighter aircraft loading standard for fatigue evaluation, mini-FALSTAFF shown in Fig. 3 [31,32]. In this Figure, normalized stress is plotted against peak-trough points of load sequence. One block of this load sequence consists of 18,012 reversals at 32 different stress levels and represents loading equivalent of 200 flights. The stress sequence for experiments reported here was obtained by multiplying with a constant reference stress value, σ_{ref} for all the peak-trough points in the entire block. Spectrum fatigue tests with various reference stress levels were conducted on both PLL and PLD composites. Tests were conducted in a computer controlled 100 kN servo-hydraulic test machine. Sinusoidal waveform with an average frequency of 3 Hz (6 reversals per second) was employed in the tests. The geometry of the fatigue test specimens used is shown in Fig. 2. For any given reference stress, the number of load blocks required to fail the test specimen, N_b was determined. Whenever a specimen failed in-between a full block, it was rounded-off to the nearest complete block number.

For prediction of fatigue life under mini-FALSTAFF spectrum load-sequence, the constant amplitude (CA) fatigue data was generated at various stress ratios. The CA fatigue tests were conducted following ASTM D3479 test standard specifications [33]. The geometry of the CA fatigue test specimen used was similar to that employed for spectrum fatigue tests as shown in Fig. 2. All the CA fatigue tests were conducted in 100 kN computer-controlled servo-hydraulic test-machines with a sinusoidal waveform at a frequency, $\nu = 3$ Hz. Tests were conducted at three different stress ratios, $R = \sigma_{max}/\sigma_{min}$ as follows: