

Variable Amplitude Fatigue Testing to Characterize Mode II Delamination in a Polymer Composite

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Abstract In this study, the mode II delamination behavior in terms of onset-of-growth and propagation characteristics under a standard variable amplitude (VA) fatigue load sequence was investigated. A special three point bend test fixture was designed and fabricated to perform fatigue tests under VA loads. Standard end notched flexure test specimens of unidirectional IMA/M21 carbon fiber composite were fabricated. A Teflon insert was used to simulate a delamination at the mid plane. The fatigue tests were conducted under a standard mini FALSTAFF VA load sequence. Tests were carried out with different reference values of loads to determine the onset-of-growth, N_{onset} . Decreasing the reference load was observed to increase the N_{onset} . Further, the delamination propagation under the mini FALSTAFF load sequence was determined in the same test set-up. It is successfully demonstrated that the test fixture could be used to apply both negative and positive fatigue loads to simulate the service loads.

Keywords Delamination · FALSTAFF · Fatigue · Composite · Three-point bending

1 Introduction

Fiber reinforced plastics (FRPs) in general and carbon fiber composites (CFCs) in particular find a wide range of applications in aircraft structures due to their excellent

mechanical properties like specific strength and specific stiffness. Although they exhibit good fatigue resistance, many structural failures have been attributed to fatigue loads in service. Unlike metals, FRPs exhibit progressive damage accumulation due to initiation and propagation of multiple types of damages occurring during fatigue. Matrix cracking, disbond, delamination and fiber break have all been shown to be the major fatigue damage mechanisms in FRPs.

Delamination is a predominant failure mechanism in laminated FRPs. Studies related to delamination primarily focus on “onset-of-growth” rather than “initiation”. This is due to the fact that defects generally exist in such composites, which act as delamination, and subsequently begin to grow under certain loading conditions and is called as onset-of-growth [1]. The loading condition could be mode I (tensile), mode II (shearing) and mode III (tearing) or mixed mode conditions. The total fatigue life of a delamination (N_f) is the sum of number of cycles for onset-of-growth (N_{onset}) and the number of cycles for propagation (N_p). Very limited studies are available on N_{onset} and N_p of a delamination [2–5] since in practice the design philosophy adopted is “no growth”. However, their knowledge would be useful in exploiting the potential of a material and yet allowing the material to “fail-safe”.

Many recent studies on the delamination behaviour of composites, both on mode I and mode II have focused on constant amplitude (CA) fatigue loading [1–8]. An elaborate study on the testing methodology, determination of N_{onset} and delamination growth rate (da/dN) both under mode I and mode II was reported in [2] and [3] respectively. Delamination study under spectrum loading or variable amplitude (VA) are seldom reported and our earlier work on understanding the onset-of-growth under spectrum loading was limited to modified spectrum load

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sequence consisting of only tensile loads [6]. Unlike mode I, delamination under mode II condition could experience both tensile and compressive loads and this has shown to significantly affect the growth rate at $R = -1$ condition [7]. Generally, mode II studies are done using end-notched flexure (ENF) specimen under a three point bend test set-up [8, 9]. However, this conventional fixture could apply only compressive or tensile loads and cannot be used in case of both tensile and compressive loading, which is generally the case in a spectrum loading. Therefore, the aim of the present work was to: (1) fabricate and evaluate a fixture that could be used to characterize mode II delamination under spectrum loading, and (2) study the onset-of-growth and propagation of mode II delamination under spectrum loading in an airframe grade IMA/M21 CFC material.

2 Experimental

2.1 Material and Specimen

The unidirectional carbon fiber/epoxy IMA/M21 prepreg of 0.18 mm nominal thickness, obtained from M/s Hexcel, was cut into 300 mm × 450 mm and laid up on a tool. Teflon sheet of 30 μm thickness was introduced at the mid thickness to create an artificial delamination in the test specimens. The composite was cured in an autoclave maintained at a pressure of 7 bar at 180 °C for 2 h. Both the heating and cooling rate were maintained between 1 and 2 °C/min [10]. The fiber volume fraction of the laminate was 59 %. The prepared laminates were ultrasonically C-scanned. ENF test specimens were cut and prepared from the laminate. Dimension of the test specimen and the loading arrangement used is schematically shown in Fig. 1.

2.2 Fatigue Testing

Constant amplitude and VA fatigue tests were carried out on an ENF specimen using a computer controlled 25 kN servo-hydraulic test machine under load control mode. A schematic of the three-point bend test set-up used for fatigue testing is shown in Fig. 1. The conventional three point bend set-up, shown in Fig. 1a, does not permit

positive to negative loading and this limitation was overcome in the new fixture through the arrangement of loading and bottom supports, as shown in Figs. 1b and 2a. The bottom supports are free to rotate in an axis perpendicular to the loading direction (Fig. 2b) while the specimen, held between the rollers, is loaded through the central loading support as shown in Fig. 2c. It is important that the mid thickness of the specimen is perpendicular to the loading axis and parallel to the bottom support axis (Fig. 1) and this was ensured using a vernier height gauge. The gap between the rollers depends on the specimen thickness and could be adjusted using the bolt and lock-nut arrangement (see Fig. 2b, c). Researchers have used a similar fixture to carry out CA fatigue [7] and quasi-static tensile and compressive tests [11]. In order to validate the new fixture, CA fatigue tests were done at a stress ratio of $R = 0.0$ using both the fixtures. The compliance of the specimen was monitored during the CA fatigue test at regular intervals and the number of cycles for onset-of-growth, N_{onset} was assumed whenever a 5 % increase in compliance value from the initial value was observed.

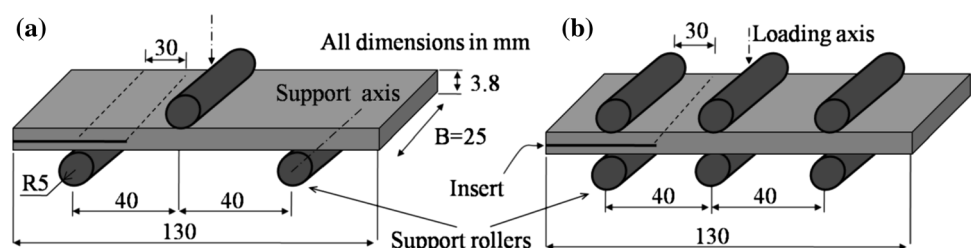
Mini-FALSTAFF, shown in Fig. 3, is a short version of the FALSTAFF load spectrum [12], and is a standardized VA test load sequence developed for the fatigue analysis of materials used for fighter aircraft. One block of mini-FALSTAFF load sequence consists of 18,012 reversals at 32 different stress levels and represents loading equivalent of 200 flights. The actual load sequence for the spectrum test was obtained by multiplying all the peak/trough points in the entire block with a reference load and tests were conducted at various such reference loads.

3 Results and Discussions

3.1 Constant Amplitude Fatigue Behavior

Constant amplitude fatigue tests were conducted using both conventional and new test fixtures. The crack driving parameter in delamination is generally calculated in terms of strain energy release rate (SERR) and is represented as G . SERR under mode II loading condition (G_{II}) is related to

Fig. 1 Dimensions of the ENF specimen tested under, **a** conventional three-point bending set-up and **b** the new fixture



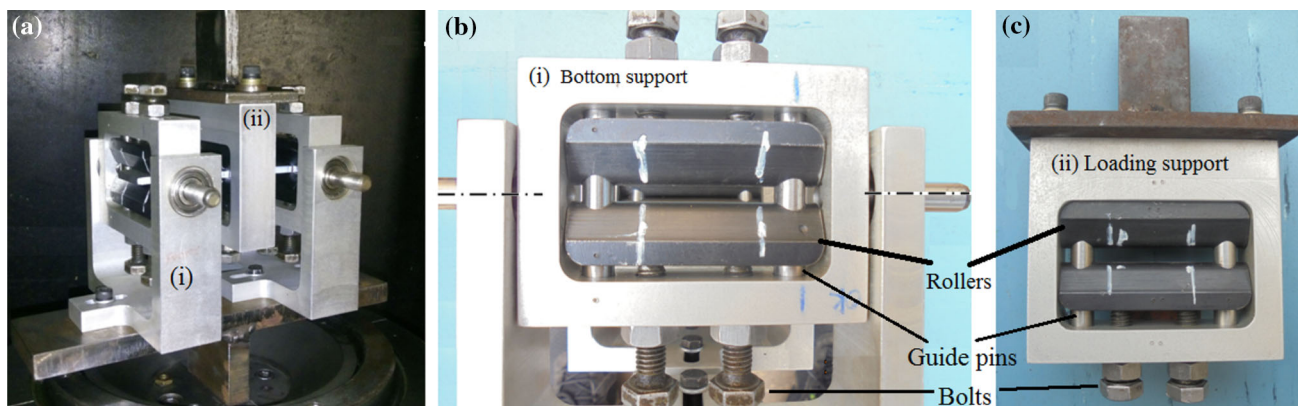


Fig. 2 a New three-point bend fixture capable of applying both negative and positive loads. b Side view of the bottom support and c the central loading support

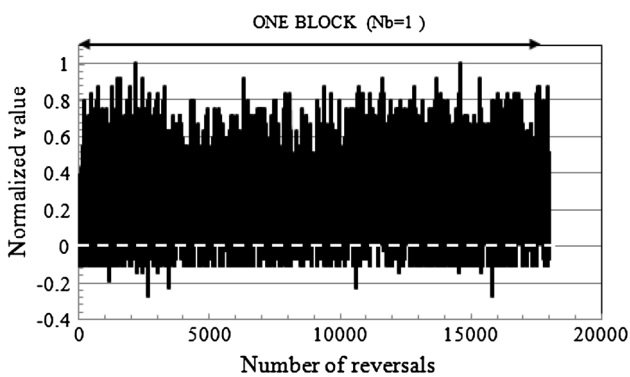


Fig. 3 Standard mini-FALSTAFF variable amplitude load sequence

the applied load (P), delamination length (a) and the width of the specimen (B) through the equation [3]:

$$G_{II} = 3mP^2a^2/2B \tag{1}$$

where, m is measured through compliance calibration technique and is the ratio of specimen compliance (C) to the cube of the delamination length ($m = C/a^3$). The onset-of-growth at various maximum SERR (G_{max}) was determined for the CFC at stress ratio $R = 0.0$. The $G_{max} - N_{onset}$ curve determined for mode II delamination of IMA/M21 CFC is shown in Fig. 4 and is similar to the $S-N$ plot in its usefulness [6]. It is clearly seen that the test results from the new fixture are comparable with results from the conventional fixture indicating that it may be used for different fatigue loading conditions.

3.2 Spectrum Fatigue Testing

Spectrum fatigue tests were done at various reference loads and the corresponding SERR, G_{Ref} , was calculated using Eq. 1. The compliance of the specimen was monitored during the spectrum test at the end of every block and the

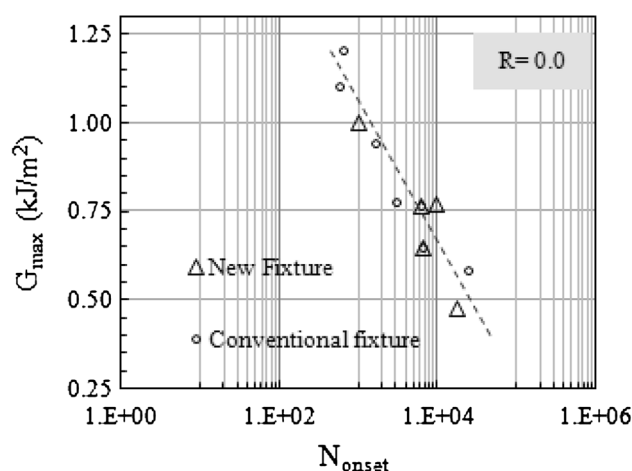


Fig. 4 Experimentally determined $G_{max} - N_{onset}$ plot comparing the results from the new fixture with conventional fixture

number of blocks for the onset-of-growth, $(N_b)_{onset}$ was assumed whenever a 5 % increase in compliance from the initial value was observed, as shown in Fig. 5a. $(N_b)_{onset}$ increased with decrease in G_{Ref} values (Fig. 5b) and is similar to the trend observed elsewhere under spectrum loading [6].

Spectrum tests were continued beyond the onset-of-growth and till the delamination reached the critical length corresponding to the critical SERR (G_{IIc}). The delamination length was determined using the compliance technique [6] at the end of every block (N_b), to get the a versus N_b plot. The complete a versus N_b plot for a particular G_{Ref} value is shown in Fig. 6. It is clear from the figure that a significant number of blocks are spent in delamination propagation (N_p) before fracture. The observed trend is similar to the ones observed by researchers under CA loading in IM7/8552 [3] and T300/5405 [4] CFRP materials.

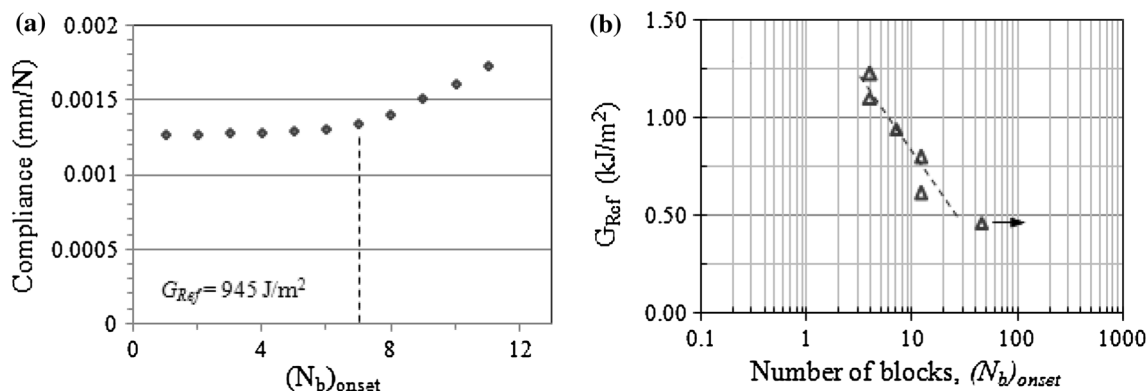


Fig. 5 a Measurement of $(N_b)_{onset}$. b Experimentally determined $(N_b)_{onset}$ under standard mini FALSTAFF

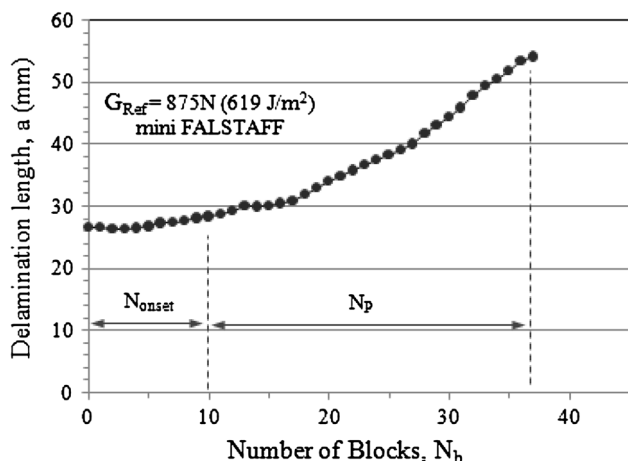


Fig. 6 Onset-of-growth and propagation of delamination at a particular G_{Ref} value subjected to mini-FALSTAFF loading

4 Conclusions

Based on the results obtained in the present investigation, following conclusions may be drawn:

- Under similar loading conditions, CA fatigue tests results from the new fixture were comparable with the results from the conventional fixture. This indicates that the fixture could be used for tension–compression fatigue tests, as well as VA spectrum tests.
- The number of blocks required for onset-of-growth, $(N_b)_{onset}$, of mode II delamination increased with decrease in the applied SERR.
- A significant amount of time (in terms of number of blocks) was spent in delamination propagation, N_p , and the results obtained could be interesting from the damage tolerance design point of view.

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Compliance with ethical standards

Conflict of interest None.

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