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Post-impact Fatigue Response of CFRP Laminates under Constant Amplitude and Programmed FALSTAFF Spectrum Loading

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Abstract

Post-impact fatigue response of Carbon Fibre Reinforced Polymer Woven Roving Mat (CFRP-WRM) laminates under constant amplitude (CA) and programmed version of FALSTAFF (Fighter Aircraft Loading STAndard for Fatigue and Fracture) is presented here. Stiffness degradation as a function of number of cycles of loading at varying percentages of strength after impact (SAI) was investigated after subjecting the specimens to 53 J of impact. The stiffness loss can be classified into three ranges: primary, secondary and tertiary. The loss of stiffness as a fraction of failure life under programmed FALSTAFF loading was observed to be less severe compared to CA loading.

Keywords:CFRP laminate, post-impact fatigue, FALSTAFF spectrum, stiffness degradation.

1. Introduction

Fiber reinforced composites are used in light-weight, safety critical structures such as aerospace structures. They are subjected to variety of operating conditions and loadings that includes fatigue loading. In addition, most often these composite structures are subjected to impact loading due to bird strike, hail storm, tool drop etc., which introduces damage in the built-up laminates. In some cases, the damages are barely visible and as a consequence,

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these structures may be operated without realizing the presence of damage in the laminates. This results in accelerated damage progression in these composite materials, which can reduce the residual strength carrying capability as well as residual life. Primary causes of damage progression are: micro-damage, transverse matrix cracking, de-lamination, and fiber-failure [1]. The purpose of this research is to examine the fatigue response of CFRP laminates in the un-impacted and impacted conditions under constant amplitude loading and for the case of an impacted laminate, under a programmed European standard Fighter Aircraft Loading Spectrum (FALSTAFF) under tension-tension loading conditions. The response of laminates to fatigue loading was evaluated through stiffness variation as a function of the number of applied cycles of loading. Highsmith and Reifsnider [2] have correlated the stiffness reduction due to fatigue cycling with transverse cracking, crack density and transverse crack growth in the laminates. The authors have proposed a critical damage state, also referred to as 'characteristic damage state'. Similar approach has been followed by Camponeschi and Stinchcomb [3], Talreja [4] and Ogin et al [5].

Hoover et al [6] conducted a study correlating the stiffness reduction during a tensile test with the crack density through a linear relationship. Interestingly, they reported a three stage damage progression: first stage where there is no transverse cracking, second stage where there is a linear stiffness degradation where almost all transverse cracks initiated and the final stage where there is a significant drop in stiffness, which is due to large scale de-lamination of the laminate. Takada et al [7] conducted fatigue studies on cross-ply carbon fiber composites to understand the phenomenon of de-lamination initiation and crack density during fatigue loading. The observed damage modes in laminates were: matrix cracking, de-lamination and fiber fracture. Matrix cracking and de-lamination lead to loss of stiffness during fatigue loading. Wharmby et al [1] studied the damage accumulation during cyclic loading through the use of digital image correlation technique and measurement of stiffness reduction. One of the advantages of stiffness measurement is that it can be on-line monitored without any test interruption (unlike the case of C-scan imaging). Salkind [8] had suggested that changes in stiffness can be used to measure fatigue damage in composites. One of the negative aspects of stiffness measurement is that it cannot clearly delineate the different types of failure mechanisms during fatigue loading, such as, matrix cracking, de-lamination. Whitworth [9] found that this method of measuring stiffness reduction can be used to build a mathematical relationship between residual stiffness and other material properties, such as, residual strength and remnant fatigue life. Stiffness reduction data was obtained for $[+/- 45/90_3]_s$ laminates and $[0_2/90_3]_s$ cross-ply CFRP laminates. The rate of stiffness reduction was found to be inversely proportional to the number of cycles to failure. The initial drop in stiffness was ascribed to the accumulation of matrix cracking while the saturation state was due to de-lamination mode of failure. It was also observed that the proportion of laminate life for which transverse cracks initiate and saturate was the same regardless of the applied load level during fatigue cycling. Most of the observations relate to constant amplitude fatigue cycling of cross-ply laminates without any defect/impact damage.

Behesty and Harris [10] studied the fatigue behavior of CFRP laminates after low velocity impact damage and observed that low velocity impact damage (1-5 J) had very little impact on tensile residual strength of composites, but the effect was significant while compression strength properties were evaluated through compression after impact tests. The authors also indicated that the constant-life model proposed by Harris [11] can be used to predict fatigue life for low energy impact damaged specimens. Clark and Van Blaricum [12] conducted spectrum loading fatigue tests on impact damaged carbon fiber composite coupons. The impact damage was introduced with 11J indentation and the post-impact damage fatigue response was monitored during a typical fighter aircraft spectrum loading using compression dominated cycles. It was observed that major cycles contribute to fatigue damage under spectrum loading compared to several of small amplitude cycles in the spectrum. Removal of small amplitude cycles did not change the outcome of damage progression during spectrum loading. Significant increase in hysteresis was observed in case of impact damaged coupons during fatigue cycling at 2-5 Hz. High damping ratios (of the order of 0.65-0.7) was observed for a severely damaged coupon cycled at 5 Hz compared to an undamaged coupon which had very low damping ratio (~ 0.057). From the above discussions, it is observed that post-impact fatigue response of composites under spectrum loading is an important area for investigation. This work concentrates on the fatigue response of carbon fiber composites subjected to tension-tension loading both under constant amplitude and under spectrum loading. The concepts of loss of stiffness provide a good measure of performance degradation of the composite material and hence this aspect would be investigated in this study.

2. Experimentation

2.1 Specimen preparation

Woven carbon fabric of 500 gsm, 0.28 mm thick (HCT 502), sourced from Hindoostan Technical Fabrics was used as the reinforcement in an epoxy resin matrix system consisting of Araldyte® LY 556 (resin) and HY 906 as the hardener. Laminates were prepared using hand layup technique, by laying up 8 layers of [0/90] fabric with epoxy between layers. The laminate was cured at 80 °C for 3 hours to obtain laminates of nominal dimension of 350 x 350 mm with a final thickness of 4.5 mm that includes thickness of woven fabric and epoxy. The test specimens were then sliced using water jet cutting machine to a finish size of 250 x 45 x 4.5 mm thickness. The GFRP end-tabs of 3 mm thickness were fixed using epoxy LY556 and hardener HY991 for tensile specimen and a few fatigue specimens (Fig. 1).

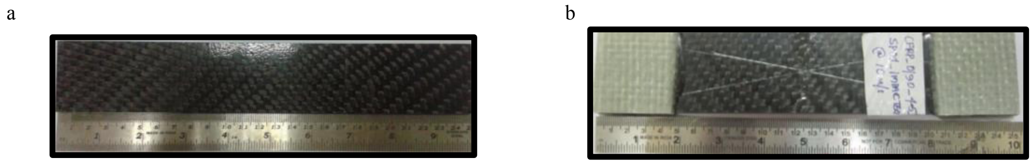


Fig. 1. (a) Pristine specimen; (b) Specimen with end tabs

2.2 Drop impact testing

An in-house developed drop-impact tester with an impactor of mass 5.2kg and hemispherical tup of nominally 16 mm diameter as shown in Figure 2 was used for causing an impact damage of 53J energy on the composite laminates. The load during impact was measured using a load cell and the displacement was measured using an LVDT that was mounted beneath the drop impactor. The data was recorded online and used for post processing. Figure 3a presents the load-displacement data obtained during one of the drop impact tests on CFRP laminates. The damage zone was observed to be concentrated on the first few layers of the laminate; Representative C-scan image of an impacted specimen is shown in Fig. 2c. Additional C-scan studies are in progress to quantify the damage zone.

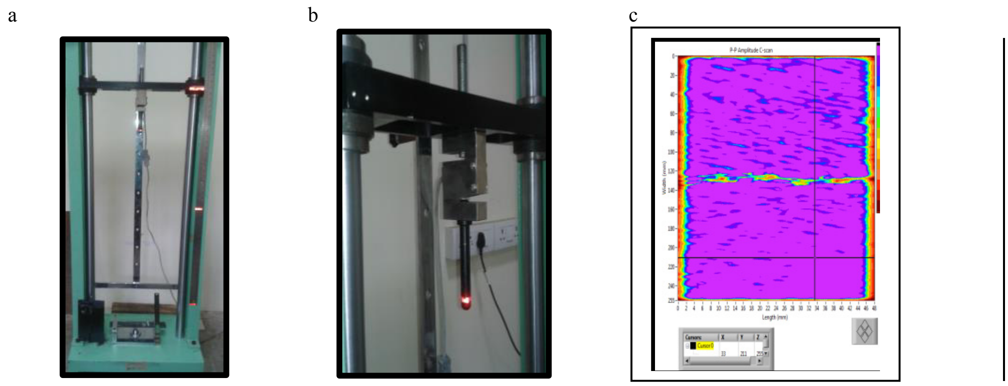
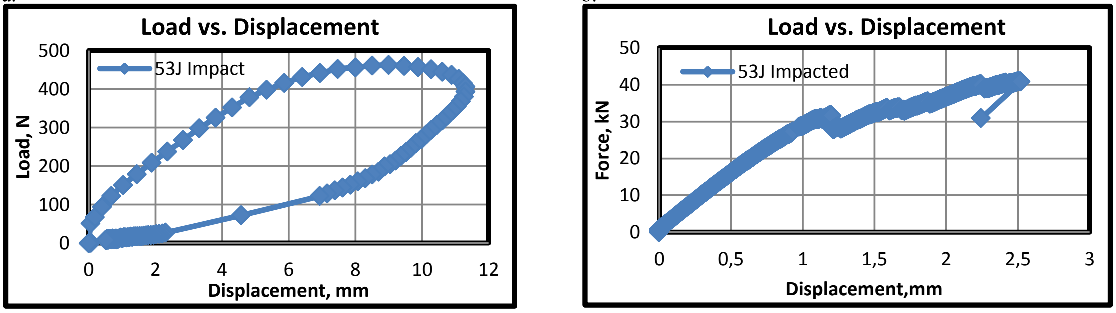


Fig. 2. (a) Drop Impact Test Set-up; (b) impactor; (c) typical C-scan image of impacted specimen.

2.3 Tensile and fatigue testing

Tensile tests were conducted on un-impacted and impacted laminate specimens using a 100 kN-MTS 810 servo-hydraulic testing machine under displacement control mode at a loading rate of 0.1 mm/min. Typically un-impacted specimens had an ultimate tensile strength of 750 MPa, while impacted specimens had a typical ultimate tensile strength of 202 MPa (~ 27 % of un-impacted ultimate tensile strength). Figure 3b shows the typical tensile test result for a post-impacted specimen.

a. b.



Fatigue tests were conducted on the same MTS 810 servo-hydraulic machine under constant amplitude (CA) sinusoidal waveform cycling at a stress ratio (R) of 0.1 at a cyclic frequency of 5 Hz as per the test matrix shown in Table 1. The load, displacement data during fatigue test was continuously monitored for post processing of stiffness. In case of constant amplitude fatigue testing, test was stopped after a run-out criterion of 10^6 cycles.

Table 1 – Test parameters for fatigue cycling

Sl. No.	Specimen Condition	Load Range (kN)	Stress range (MPa)	Test Condition
1	Un-impacted	4.5 – 45	22.2 – 222.2	CA
2	Un-impacted	6.0 – 60	29.63 – 296.3	CA
3	Un-impacted	7.5 – 75	37 – 370.37	CA
4	Impacted @ 53 J	1.2 – 12	5.9 – 59.26	CA
5	Impacted @ 53 J	1.8 – 18	8.88 – 88.88	CA
6	Impacted @ 53 J	2.25 – 22.5	11.11 – 111.11	CA
7	Impacted @ 53 J	2.4 – 24	11.85 – 118.5	CA
8	Impacted @ 53 J	2.6 – 26	12.84 – 128.4	CA
9	Impacted @ 53 J	0 – 24	0 – 118.5	FALSTAFF

The programmed FALSTAFF spectrum as detailed in Ref. 13 was applied on one of the specimens to evaluate the fatigue performance under spectrum loading. The 18 major loads of FALSTAFF spectrum were retained in their original order and all minor loads were converted as equivalent block of marker loads as per Table 2 and the same was applied after every major load. All negative loads were truncated to zero for the FALSTAFF spectrum loading. As the specimens were tested without anti-buckling guides, the laminate strength and stiffness in compression loading was not adequate, hence, all FALSTAFF experiments were conducted under tension-tension loading.

3. Results

The stiffness of pristine specimens before fatigue cycling was estimated from the first cycle of fatigue loading and is used as a reference for each stress level of fatigue testing. This defines the initial stiffness of the specimen. Stiffness data at periodic intervals of cycles was estimated from unloading segment of load-displacement data over a window of 90-50% of maximum stress applied during fatigue cycling. In case of FALSTAFF spectrum loading, stiffness data was estimated over the window of 85-50% maximum stress for a single cycle of constant amplitude cycle that was applied immediately every block of 200 flights loading of FALSTAFF spectrum.

Table 2 – Marker block loading between 18 major loads of FALSTAFF spectrum (Programmed FALSTAFF) [13]

Sl.No.	P_{max}	P_{min}	No. of cycles
1	83%	0	2
2	75.5%	0	4
3	70%	0	10
4	65.5%	4.21%	17
5	58%	8.15%	35

Figure 4 shows the stiffness (K) versus number of cycles graph for the impacted and un-impacted CFRP specimens tested under constant amplitude loading and FALSTAFF spectrum loading. 10^6 cycles was considered as criterion for test run-out. The stiffness of specimens as estimated from unloading compliance was found to vary over a small range for both impacted and un-impacted specimens; higher stiffness values were found for fatigue tests with lower peak loads, both for impacted and un-impacted specimens. This could be due to the non-linear nature of stress-strain response of the laminate; higher non-linearity in stress-strain response sets in with increased loads.

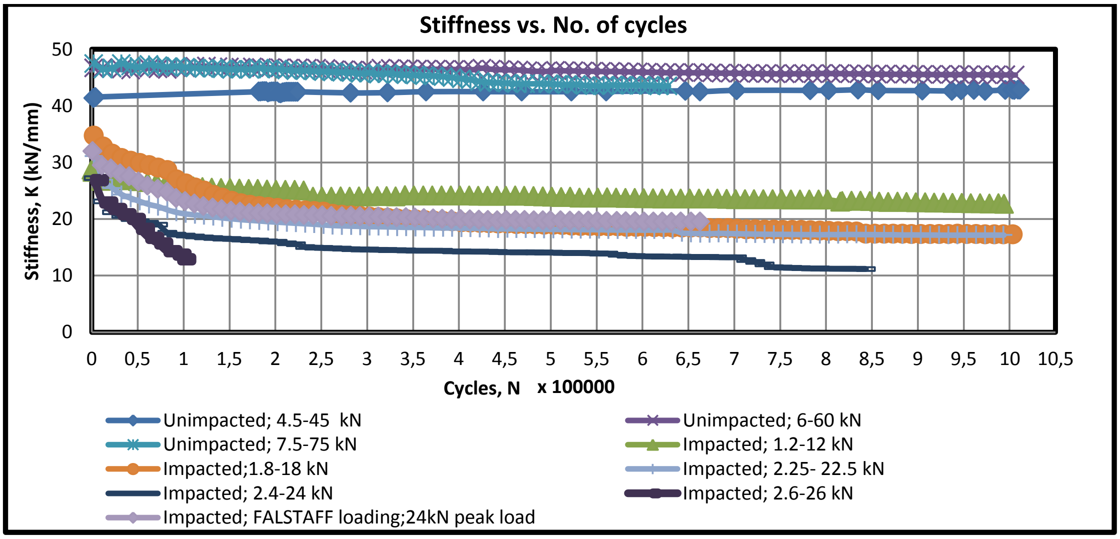


Fig. 4 Stiffness variation with Cycles

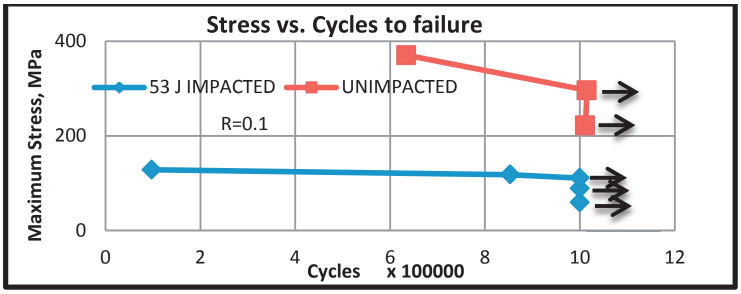


Fig. 5 S-N curve for CFRP specimens

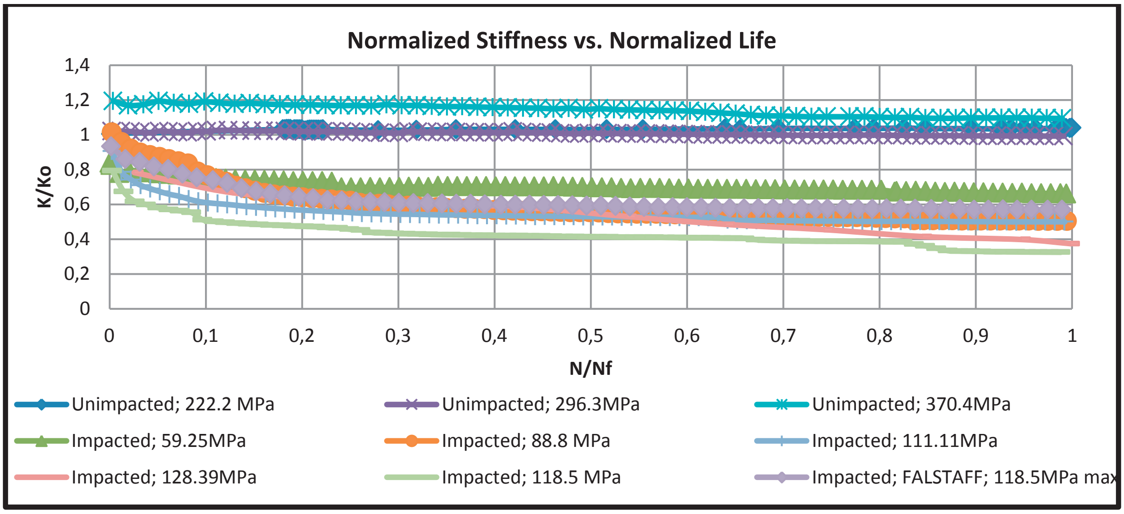


Fig. 6 Normalized stiffness vs. Normalized life graph

Figure 5 presents the maximum stress vs. cycles to failure for impacted and un-impacted CFRP specimens under constant amplitude loading. It can be inferred that after impact damage, the stress for a given failure cycles has decreased by three times (~ 120 MPa and 370 MPa for a failure life of 800000 cycles). There is a significant reduction in fatigue strength due to prior impact damage. This reduction is comparable to the reduction in static strength loss due to impact loading (27% of UTS of un-impacted specimens for post impacted specimens). This also points to the possibility of deriving post-impact fatigue strength from static tensile tests. The stiffness data was normalized to stiffness prior to fatigue cycling and cycles data was to failure life (or 10^6 cycles in case of run-out tests). Figure 6 presents the normalized stiffness (K/K_0) versus normalized cycle (N/N_f) data for all specimens tested. It can be inferred from the two figures that the stiffness varies as three regions: initial rapid decrease, followed by steady state and final drop in stiffness prior to failure. Figure 7 presents the graph of maximum cyclic stress level versus life fraction at which the steady state stiffness response was observed (N/N_f@ 0 K rate). It may be noted that steady state stiffness response indicates the region where the transverse cracking commences. It is observed that higher number of cycles is required for the on-set of steady state stiffness for specimens subjected to higher levels of stresses in both the specimen conditions (impacted, un-impacted).

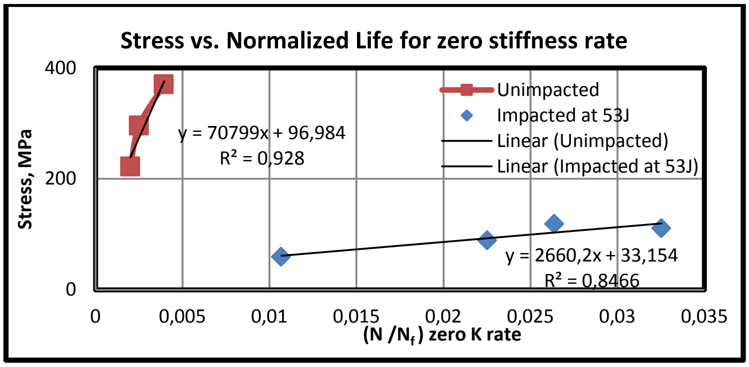


Fig. 7 Comparison of Stress vs. Normalized Life for impacted and un-impacted specimens

Figure 8 presents the variation of rate of change of stiffness (first derivative of stiffness with cycles of loading) versus cycles of loading for specimens tested at same peak stress under constant amplitude loading and FALSTAFF spectrum loading. It is observed that the onset of transverse cracking in case of FALSTAFF spectrum loading is earlier when compared to constant amplitude loading. Figure 9 presents the comparison of normalized stiffness (ratio of stiffness after 2500 cycles to stiffness prior to fatigue cycling) as a function of normalized stress (% of ultimate tensile strength prior to fatigue cycling) for un-impacted and impacted specimens. It is noted that with the increase in fatigue stress level, the stiffness of impacted specimen decreases, possibly due to the deterioration of material due to micro-cracks. In case of un-impacted specimen, the stiffness does not show much of degradation – on the contrary, there is a marginal increase in stiffness with applied stress level, which could be due to the strain hardening nature of the polymer-matrix system. As all constant amplitude fatigue tests were conducted at a fixed cyclic frequency of 5 Hz, one could not ascribe the change in stiffness to strain rate effects.

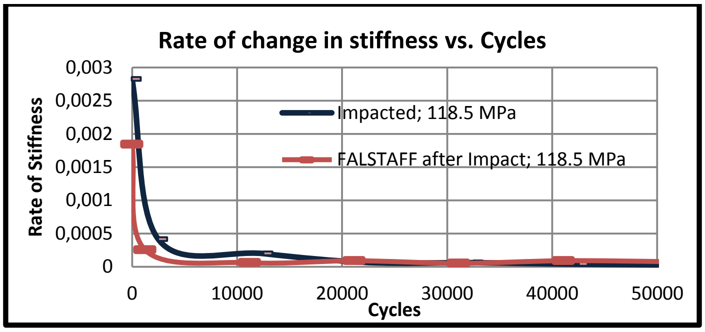


Fig. 8 Variation of Rate of Change of Stiffness versus Cycles

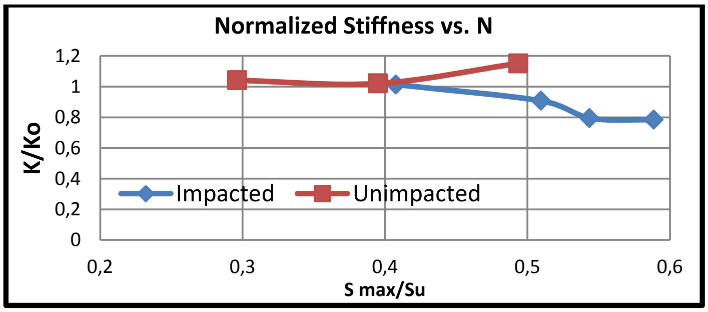


Fig. 9 Normalized Stiffness variation with Normalized Stress fraction

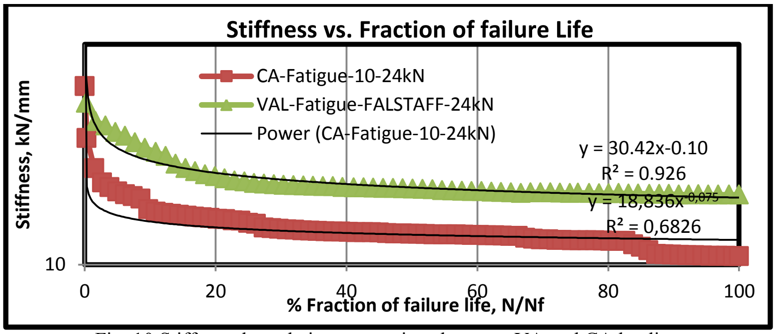


Fig. 10 Stiffness degradation comparison between VA and CA loading

Figure 10 presents the comparison of stiffness degradation for two tests conducted at the same maximum stress level – one from constant amplitude loading and another from FALSTAFF spectrum loading. It is observed that the stiffness degradation during FALSTAFF spectrum loading is much less compared to the constant amplitude loading. The steady state stiffness value under FALSTAFF spectrum loading was observed to be about 70% of the stiffness value during constant amplitude loading. This could be due to the fact that FALSTAFF spectrum loading has several cycles of small amplitude that are much less damaging on the composite specimen. Further studies are in progress to characterize the damage through ultrasonic C-scan, electron microscopy and to understand the effect of loading sequence on fatigue damage in composite laminates.

4. Summary

This paper presented the results of fatigue testing on woven mat CFRP laminates subjected to constant amplitude loading before and after impact damage and under FALSTAFF spectrum loading after impacting the specimens with drop weight impactor. The loss of stiffness as a function of applied cycles was continuously tracked and is used to observe the three regions of damage, viz., on-set of transverse cracking, de-lamination and final failure. It is observed that there is greater degradation in stiffness with applied stress levels for impacted specimens compared to un-impacted specimens. The stiffness degradation is higher in case of constant amplitude loading compared to FALSTAFF spectrum loading for specimens tested at same peak stresses.

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