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PROGRESSIVE DAMAGE ACCUMULATION PROCESS OF CFRP CROSS-PLY LAMINATES DURING THE EARLY FATIGUE LIFE

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Abstract: *The present work aims at investigating the progressive damage accumulation process of CFRP laminates in an interactive scheme, with a special focus on the early fatigue life where mainly matrix-dominant damage accumulates and stiffness degrades significantly. An in-situ damage monitoring system, containing edge observation, digital image correlation and acoustic emission techniques, was established to characterize and quantify the accumulation of transverse cracks and delamination. Two cross-ply configurations ($[0/90_2]_s$ and $[0_2/90_4]_s$) and different stress levels were involved in the experimental campaign. Dependent crack ratio was proposed to reflect the interaction among transverse cracks, and saturated crack density was used to represent the interactive level between transverse cracks and delamination. Results showed that generation of transverse cracks and their interaction govern the early fatigue damage accumulation of the $[0/90_2]_s$ laminates, while not only the interaction among cracks but also the interaction between both damage mechanisms were observed for the $[0_2/90_4]_s$ laminates.*

Keywords: Delamination; Fatigue damage; Stiffness degradation; Transverse crack

1. Introduction

When subjected to fatigue loading, composite laminates have been recognized to experience a progressive damage accumulation process, which is initially dominant by off-axis cracking, then followed by delamination and finally ended by fiber breakage. Accordingly, a three-stage stiffness degradation is presented in a rapid-slow-rapid manner, and each stage is dominated by one damage mechanism: Stage I - off-axis cracks; Stage II - delamination, Stage III - fiber damage.

Based on this non-interactive damage scheme, a gradual stiffness degradation of 90 plies was performed to reflect the transverse crack evolution of cross-ply laminates within Stage I, which was then terminated by a sudden 90-ply discount when reaching the saturation of transverse cracks in the progressive damage model established by Shokrieh and Taheri-Behrooz [1]. Also, Pakdel and Mohammadi [2,3] regard the moment of the onset of matrix crack saturation as the moment of the initiation of delamination when higher energy is released by the growth of delamination than the multiplication of matrix cracks; then, they formulated a competition criterion considering different damage modes to predict the saturated crack density of laminates.

As extensive efforts have been put on the in-situ damage monitoring through experiments, it is found that multiple mechanisms could coexist and interact in a synergistic or competitive way. For instance, delamination could initiate within Stage I, even before the initiation of off-axis cracks [4–6]; both delamination and fiber damage could occur within Stage III which may form either delamination dominant or fiber dominant damage state [7]. Besides the interaction between different damage mechanisms, the interaction within the same damage mechanism, like matrix cracks, could also be significant for laminates [8]. Therefore, an interactive damage scheme, considering the above-mentioned damage interaction, should be proposed for characterizing the progressive damage accumulation process of laminates under fatigue loading.

In view that cross-ply laminates usually show the most of stiffness degradation within Stage I, the focus of present study is their interactive damage accumulation process during the early fatigue life. Around 30 specimens with two ply configurations, $[0/90_2]_s$ and $[0_2/90_4]_s$, were tested under tension-tension fatigue loading at different stress levels. An in-situ damage monitoring system which contains edge observation by digital cameras, digital image correlation and acoustic emission techniques was used to investigate the accumulation of transverse cracks and delamination, the interaction among transverse cracks, and the interaction between transverse cracks and delamination for both ply-configurations.

2. Experimental methods

2.1 Material and specimen design

Unidirectional (UD) Prepreg, named Hexply® F6376C-HTS(12K)-5–35%, with a nominal thickness of 0.125 mm, was used to fabricate cross-ply laminates in the dimension of 250 × 25 mm according to ASTM D3479/D3479M-19 standard [9]. Thick paper tabs were glued on the clamping region of the specimen with a 50 mm length, using cyanoacrylate adhesive. Details about the material properties of UD lamina and manufacturing process can be found in [5,6].

2.2 Test set-up and load conditions

Figure 1 shows the experimental set-up: a 60 kN fatigue machine, two pairs of cameras and acoustic emission sensors. One pair of cameras in the front is to obtain the strain field of the gauge region (~80 mm) using digital image correlation (DIC) methods. Another pair of cameras at left and right sides is to monitor transverse cracks at 90 plies and interlaminar cracks at 0/90 interfaces from the edge view, which was later quantified or localized by an image processing algorithm [10]. Delamination area can be obtained by the area of transverse strain concentration from DIC, which shows the potential to reflect the separation between 0 and 90 plies [5].

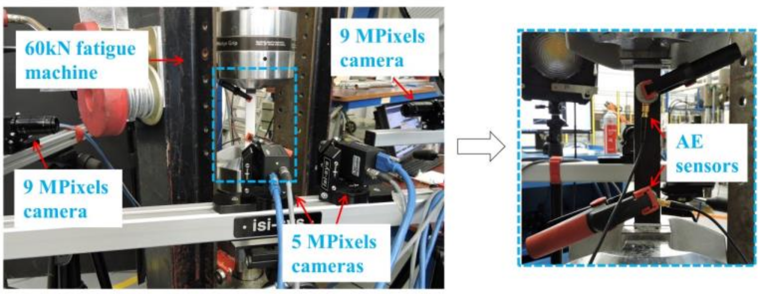

Figure 1. Test set-up.

Cyclic loading with a constant stress amplitude was applied on the specimen with a stress ratio 0.1 and frequency 5 Hz. Every 500 cycles, an unloading-loading tensile ramp in two seconds was performed where the image acquisition of both pairs of cameras was triggered. For the $[0/90_2]_s$

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laminates, maximum stress levels at 77%, 70% and 63% of ultimate tensile strength (UTS) were applied, and tests executed till the evolution of transverse cracks reached a saturated state. For the $[0_2/90_4]_s$ laminates, 74%, 70%, 66% and 63% of UTS were selected as the maximum stresses and tests stopped when the stiffness degradation approached the stable phase of the second stage. The run-off of all fatigue tests was set to ∼1e6 cycles.

3. Results

3.1 $[0/90_2]_s$ laminate

As shown in Figure 2, almost no delamination was detected at the region between two tabs in comparison with the intact one, according to the C-scan results after tests. Besides, no significant interlaminar cracks were observed from images captured at the edge view. Apparently, thin 90 plies with 0.5 mm thickness restrain the growth of delamination, and transverse cracks were the only dominant damage mechanism in the early fatigue life.

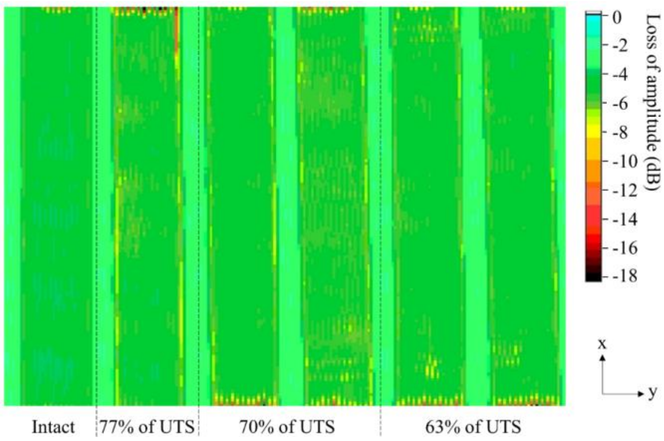

Figure 2. C-scan results for the $[0/90_2]_s$ laminates.

A bi-linear trend of stiffness degradation and crack density as a function of fatigue cycles were observed, as an example of the stress level at the 70% of UTS plotted in Figure 3. A considerable reduction of both the growth rate of crack density and the degrading rate of stiffness occurs when the crack density is relatively high (~ 0.8 mm^{-1}). This phenomenon should be attributed to the significant interaction among transverse cracks that the stress redistribution around prior cracks increased the resistance for the formation of new cracks.

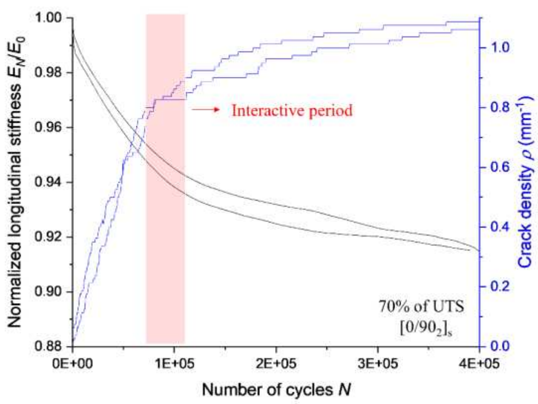

Figure 3. History of stiffness degradation and crack density evolution for the $[0/90_2]_s$ laminates.

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3.2 $[0_2/90_4]_s$ laminate

Different form the $[0/90_2]_s$ laminates, significant delamination growth was observed during the early fatigue life of $[0_2/90_4]_s$ laminates. For an example of the specimens which shared a similar stiffness degrading trend at 70% of UTS, Figure 4 presents the accumulation of transverse cracks, delamination growth along edges and within the specimen as a function of fatigue cycles.

Instead of the moment after the saturation of transverse cracks, delamination initiated and started to grow significantly at the very early fatigue life when a low crack density was presented (~0.05 - 0.2 mm^{-1}). The saturation of transverse cracks, known as the characteristic damage state, occurred before the stiffness degradation reached a stable phrase, where the mean value of fatigue cycles at the end of Stage I among specimens is marked as a dash line in Figure 4. At CDS, delamination grew considerably along the edges, while it seldom propagated within the specimens in view that the delamination area is less than 10% (see Figure 4(d)).

From the initiation of delamination to the saturation of transverse cracks, the interactive period occupied about the half of fatigue cycles at Stage I, which shows a remarkable degradation of stiffness. After the saturation of transverse cracks, delamination growth along the edges became slow and gradually approached a fully delaminated state; however, delamination growth with the specimens kept a seemingly linear increase till the end of Stage I.

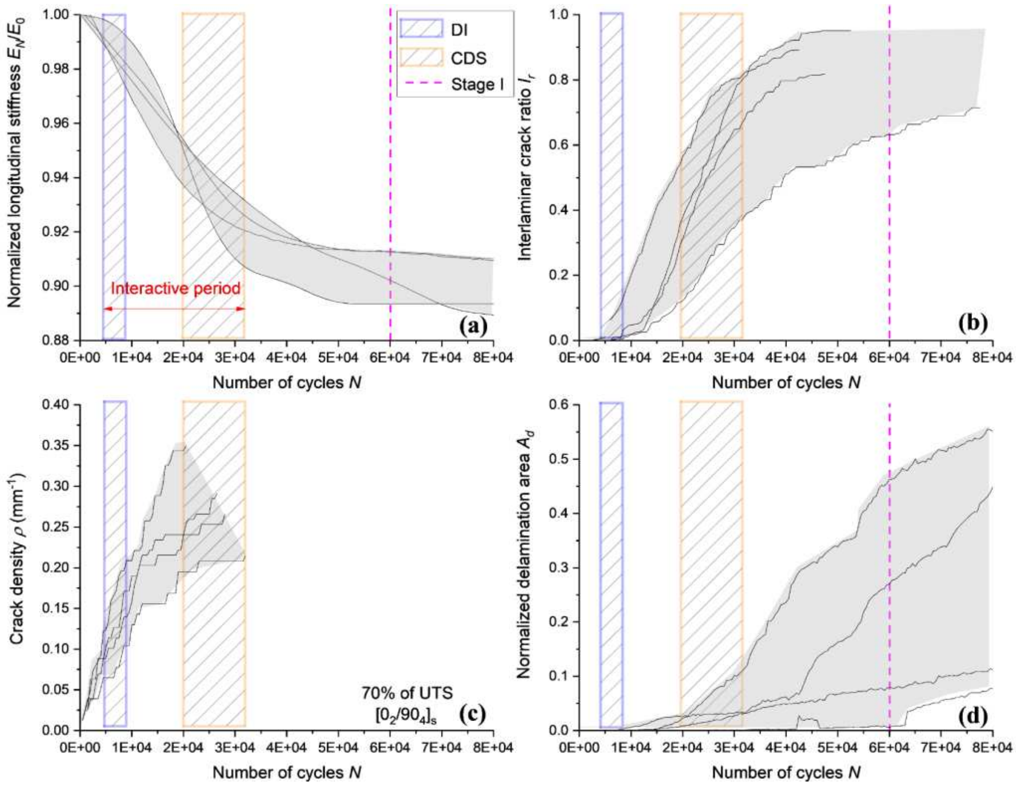

Figure 4. History of stiffness degradation (a), delamination growth along the edge(b), crack density evolution(c) and delamination growth within the specimen (d). (DI - delamination initiation; CDS - characteristic damage state)

4. Discussions

4.1 Interaction between dependent and independent cracks

To investigate the interaction among transverse cracks, dependent and independent cracks are classified by whether they occurred at a stress redistributed region, according to a critical crack spacing from 2D finite element modelling. This model implements two seam creak to simulate the stress sate of cracked region at the maximum cyclic stress, as an example of the $[0/90_2]_s$ laminates shown in Figure 5. By changing the crack spacing *d*, it is found that the axial stress of 90 plies remains the applied level at the middle of two seam cracks when *d* is larger than 2.5 mm and 4.5 mm for the $[0/90_2]_s$ and the $[0_2/90_4]_s$ laminates respectively. Therefore, the minimum or critical crack spacing for a new independent crack to be generated between these two seam cracks should be 2.5/2 = 1.25 mm and 4.5/2 = 2.25 mm at the $[0/90_2]_s$ and the $[0_2/90_4]_s$ laminates respectively.

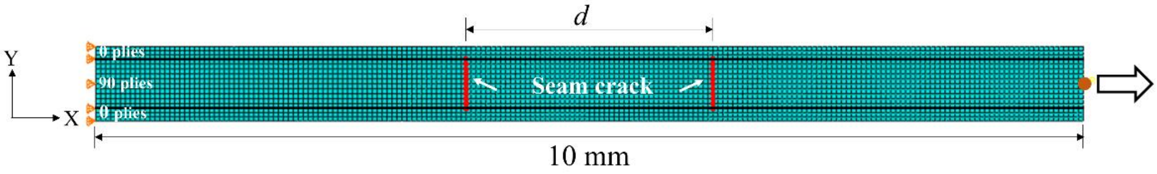

Figure 5. Finite element model for the cracked $[0/90_2]_s$ laminate, including boundary and loading conditions, and geometry dimensions.

After classifying the type of cracks based on the critical crack spacing, the maximum number of independent cracks at CDS for the $[0/90_2]_s$ laminates is about twice of that for the $[0_2/90_4]_s$ laminates. Besides, a dependent crack ratio r_d can be obtained which is the ratio of the maximum number of dependent cracks to the maximum number of independent cracks at CDS. r_d ranges approximately from 1.2 to 1.6 and from 0.1 to 0.7 for the $[0/90_2]_s$ laminates and the $[0_2/90_4]_s$ laminates respectively. This indicates more dependent cracks were generated than the independent cracks for thin 90 plies, as a result of severer interaction among transverse cracks.

4.2 Interaction between transverse cracks and delamination

Competitive relation between transverse crack generation and delamination propagation is found for the $[0_2/90_4]_s$ laminates, as specimens with a low saturated crack density usually presents a larger delamination growth. To further understand interaction between both damage mechanisms, Figure 6 plots delamination growth along the edge when crack density increases.

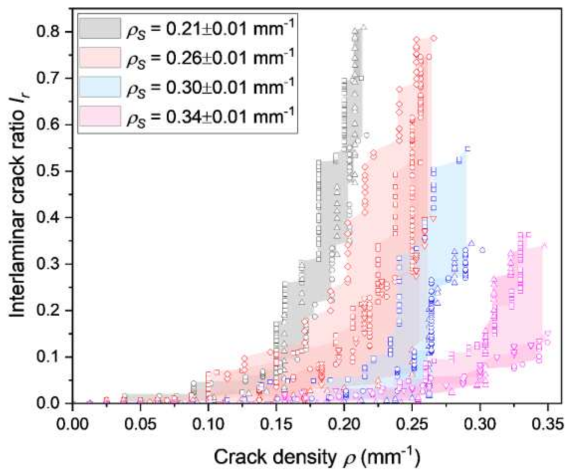

Figure 6. Interlaminar crack ratio (a) & normalised delamination area (b) versus crack density.

In Figure 6, specimens presenting a similar saturated crack density were grouped for all stress levels, and it shows that a faster growth of delamination with the increase of crack density occurs for specimens with a low saturated crack density. This further indicates that saturated crack density can be used to represent the interactive level between transverse cracks and delamination.

5. Conclusions

The progressive damage accumulation process under tension-tension fatigue loading is characterized and investigated for two types of cross-ply laminates, considering the interaction among transverse cracks and interaction between transverse cracks and delamination. The main conclusions are listed as follows:

- Dependent crack ratio can be used to reflect the interaction among transverse cracks, and it is severer at thin 90 plies than thick 90 plies for cross-ply laminates.
- Transverse cracks and delamination interact each other in a competitive way, which is more significant for cross-ply laminates with thick 90 plies; saturated crack density can represent the interactive level between both damage mechanisms.
- An interactive damage scheme is needed for describing the progressive damage accumulation of laminates under fatigue loading.

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