FATIGUE BEHAVIOR OF UN-NOTCHED AND OPEN-HOLE QUASI-ISOTROPIC PSEUDO-DUCTILE THIN-PLY CARBON/GLASS HYBRID LAMINATES

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ABSTRACT

This paper investigates the fatigue behavior of un-notched and open-hole Quasi-Isotropic (QI) thin-ply interlayer hybrids made of thin-ply T300 carbon/epoxy plies sandwiched between standard thickness S-glass/epoxy plies. Samples were initially quasi-statically loaded to failure to determine the critical stress level (pseudo-yield stress (σ_{py})) at which significant damage starts, i.e. multiple fragmentation of the carbon plies. Quasi-static results showed successful pseudo-ductility and notch–insensitivity before the final failure. The hybrid configurations were loaded at 4 Hz in tension–tension fatigue at different percentages of the σ_{py} below that required to cause significant damage. It was observed that, for the un-notched samples cycled at 80% of the σ_{py}, there is a small stiffness reduction from the early cycles caused by matrix cracking, and there is little stiffness reduction up to 100,000 cycles. By increasing the stress level to 90% of the σ_{py}, there is a gradual stiffness reduction due to the appearance of the fragmentation and delamination which leads to the failure of the un-notched samples after 10,000 cycles. A similar behavior was observed for the open-hole laminates, where initially matrix cracking and subsequently some stiffness reduction were observed for the low stress level (50% of the σ_{py}), with no more stiffness reduction up to 100,000 cycles. However a gradual delamination growth was observed for the high stress level (70% of the σ_{py}), which leads to the final failure after 30,000 cycles. Overall good fatigue performance of pseudo-ductile hybrid composites, with gradual fatigue damage growth was observed, that shows their applicability for industrial applications.

1 INTRODUCTION

There is rapid expansion of composite use in applications such as wind turbine blades, sporting goods and aero structures due to their excellent properties [1-4]. Conventional composites such as carbon fibre reinforced plastics have outstanding mechanical properties: high strength and stiffness, low weight, and low susceptibility to fatigue failure. Despite these advantages, failure in conventional composites is usually sudden and catastrophic, with insufficient warning and low residual load bearing capacity. This unfavourable failure character results in conservative structural design incorporating cautious limits preventing the full exploitation of the outstanding mechanical performance of a whole family of materials [5].

Recently, Unidirectional (UD) and Quasi Isotropic (QI) thin-ply hybrids with different types of low strain and high strain fibres were introduced that generated the desired nonlinear stress–strain response and pseudo-ductility that avoids catastrophic failure in laminated composites [6-7]. This hybridization concept was found useful in improving the notch sensitivity that is another important limiting factor in conventional composite laminates [7]. The pseudo-ductility and notch insensitivity result from subcritical damage mechanisms, i.e. fragmentation and stable delamination, which prevent catastrophic failure of the hybrid composite after the first carbon layer fracture. These damage mechanisms are illustrated schematically in Figure 1 for a three-layer UD hybrid laminate made from standard thickness glass/epoxy and thin-ply carbon/epoxy.

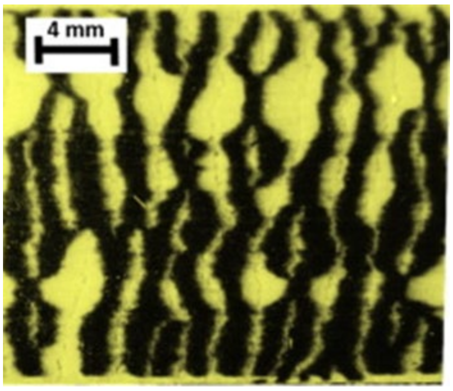

Figure. 1. A microscopic image from the surface of typical 2TR30-S-glass/epoxy laminate [6].

Appropriate material properties, and suitable values of relative thickness, i.e. the ratio of thickness of low strain material to high strain material and absolute thickness of low strain material, need to be selected for an optimal design [7].

In order to apply these pseudo-ductile hybrid composites in real-life applications, their fatigue should be understood. Previously the fatigue behavior of a UD hybrid composite was investigated and it was concluded that the UD composite has a good resistance against cyclic load even after the appearance of damage, and only a gradual increase in damage was observed over thousands of cycles [8]. However, most composite structures require multi-directional laminates. For this purpose, QI composite plates made of thin-ply carbon/glass hybrid laminates was introduced that show pseudo-ductility in all fibre orientations under tensile loading [9]. Cutouts and holes are also necessary for the geometry and assembly of composite sub-components and they weaken the laminate. Local subcritical damage, i.e. dispersed delamination and fragmentation, resulted in notch insensitivity in quasi-static tensile loading of QI thin-ply pseudo-ductile hybrids [7, 10]. These subcritical damage mechanisms may act as stress concentrations and weaken the composite's fatigue performance. As a result there is a need to understand the fatigue behaviour of these multi-directional pseudo-ductile hybrids in un-notched and notched conditions.

This study investigates the fatigue behaviour of the multi-directional pseudo-ductile thin-ply hybrid composites. Both un-notched and open-hole hybrids made of thin-ply T300 carbon/epoxy plies sandwiched between standard thickness S-glass/epoxy plies are investigated. The investigated laminates showed a successful pseudo-ductile un-notched behaviour with improved notch-insensitivity under quasi-static tensile loading. Good fatigue resistance and gradual fatigue damage growth were observed for both un-notched and open-hole configurations, showing their applicability for industrial applications.

2 EXPERIMENTAL

2.1. MATERIALS AND DESIGN

Properties of the two prepregs that were used in the experimental design are listed in table 1. Some of these are estimates, but they are sufficient to enable appropriate combinations of materials to be selected. UD S-glass/913 epoxy prepreg supplied by Hexcel was used as the high strain materials of the hybrid laminates. The low strain material was thin UD carbon prepreg, T300/epoxy (SkyFlex USN020A), from SK Chemicals (South Korea).

Table 1: Properties of the applied prepregs.

Prepreg type	S-glass/913epoxy [11]	T300/K50 120°C epoxy[a]
Fibre modulus (GPa)	88	230[b]
Prepreg fibre direction Modulus, E11 (GPa)	45.7	101.7
Fibre failure strain (%)	5.5	1.5
Cured nominal thickness (mm)	0.155	0.029
Fibre mass per unit area (g/m^2)	190	22
Fibre volume fraction (%)	50	43
Supplier	Hexcel	Sky Flex

a. These values are experimentally measured from a SkyFlex USN020A prepreg with the same elastic modulus but with a similar type of fibre made by a different manufacturer [12].
b. This value is based on T300 Data Sheet [13].

The investigated layups are schematically illustrated in Figure 2a and listed in Table 2, where, in the layup column, the first numbers show the orientations of the plies in degrees. This is an orientation-dispersed layup in which non-hybrid multi-directional S-glass/epoxy and T300-carbon/epoxy sub-laminates were put together to build the hybrid laminate. The orientation-dispersed method is considerably better to decrease interlaminar stresses at the free-edges and to suppress free-edge delamination compared to the orientation-blocked concept as discussed in [14].

The layups were designed using damage mode maps and choosing appropriate values of absolute and relative thicknesses of the carbon fibre plies. More results regarding the design inputs can be found in our previous study [7]. The resulting damage mode maps with the calculated boundaries between the different regions are illustrated in Figure 2b. The terms “Relative carbon thickness” and “Carbon thickness” are referring to the thickness of the carbon layers divided by the total thickness of the laminate, and the absolute thickness of the carbon layers that are sandwiched between the glass layers, respectively. The colours represent the expected amount of pseudo-ductile strain ε_d which is defined here as the extra strain between the final failure point and the initial slope line at the failure stress level as shown in Figure 3. The thickness and proportion of carbon plies in the investigated layup is in the Fragmentation and Dispersed Delamination (Frag. & Del.) region. Therefore, the damage scenarios in this laminate are expected to be fragmentation in the low strain material followed by dispersed delamination and then high strain material failure. Please note that the damage mode maps are obtained for the un-notched samples and damage mechanisms in the notched configurations might be slightly different.

Table 2: Investigated cases.

Layup	Laminate thickness [mm]
$[60_{\text{S-glass}}/\text{-}60_{\text{S-glass}}/0_{\text{S-glass}}/0_{\text{T300-carbon}}/60_{\text{T300-carbon}}/\text{-}60_{\text{T300-carbon}}]_s$	1.10

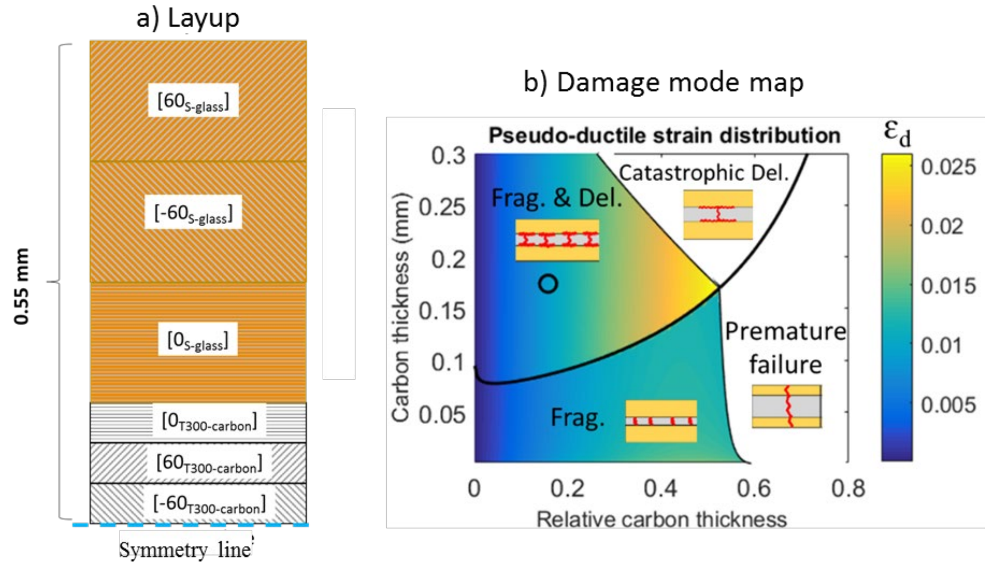

Figure 2. a) Schematic of the investigated layups, the brown and black colours are representative of the S-glass and T300-carbon, respectively. b) Distribution of pseudo-ductile strain for the investigated configurations.

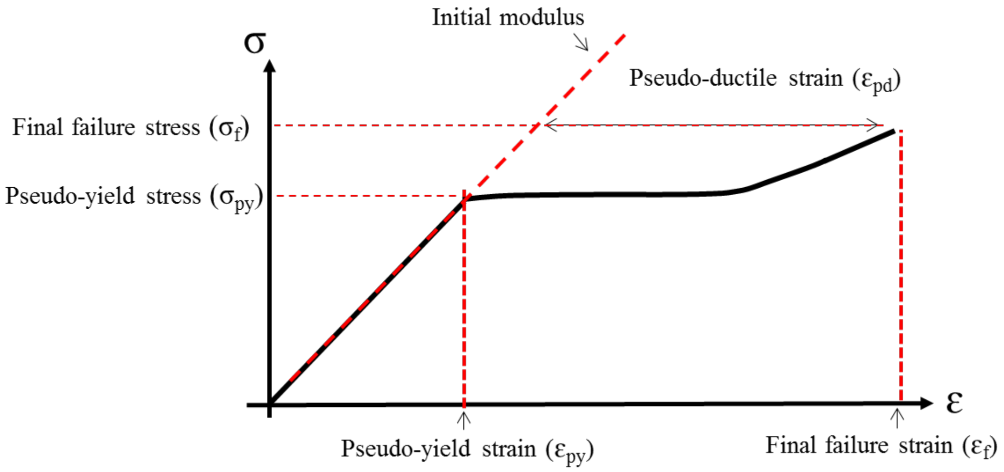

Figure 3. Schematic of the stress–strain graph of a thin-ply hybrid with pseudo-ductility.

2.2. SPECIMEN MANUFACTURING

The resin systems in the prepregs were K50 (SK chemicals) and 913 (Hexcel), both have a cure temperature recommended by the suppliers of 120°C. The resins were found to be compatible, although no details were provided by the suppliers on their chemical formulations. Good integrity of the hybrid laminates was confirmed during test procedures and no phase separation was observed on cross sectional micrographs.

Fabrication of the specimens was done using a diamond cutting wheel. As shown in Figure 4, the 3 mm nominal size open-hole samples were fabricated with a diamond drill on a CNC milling machine. End tabs made of 2 mm thick woven glass/epoxy plates supplied by Heathcotes Co. Ltd. were bonded to the specimens using a two component Araldite 2000 A/B epoxy adhesive supplied by Huntsman; the components were mixed with the volume fraction ratio of 100: 50 for A: B respectively and cured for 120 minutes at 80 °C inside a Carbolite oven.

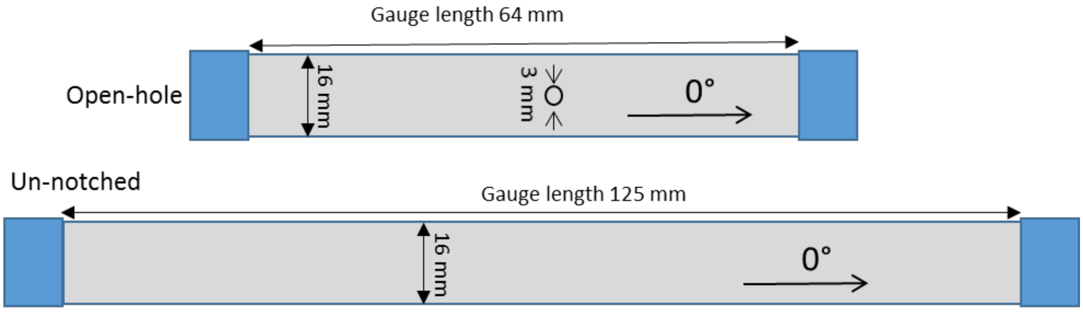

Figure 4. Schematics of the a) Open-hole, and c) Un-notched specimens.

2.3. TEST PROCEDURE

Quasi-static tensile testing of the un-notched and open-hole laminates was performed under uniaxial loading with displacement control using a crosshead speed of 1 mm/min for the un-notched laminates and 0.5 mm/min for the open-hole laminates, on a computer controlled Instron 8801 type 100 kN rated universal hydraulic test machine with wedge-type hydraulic grips. The reason for the different loading rates was to get similar strain rates for the different length specimens. The reason for a shorter length for the open-hole samples, compared with the un-notched samples, was to make more samples from the fabricated plates, therefore saving the raw materials and manufacturing cost, since the length of the specimen will not affect failure starting at the hole. A 25 kN load cell was used for better resolution in the expected load range.

Tension-tension fatigue tests were performed using the same Instron machine below the pseudo-yield stress (σ_{py}) that is defined as the stress level at which the tensile response has a significant deviation from linear elastic behavior as schematically shown in Figure 3. Un-notched specimens were fatigued at two different stress levels below σ_{py}, 90% and 80% of σ_{py}, while open-hole specimens were fatigued at 70% and 50% of σ_{py}. Specimens were fatigued till failure or 100000 cycles, whichever happened first. All fatigue tests were conducted under load control by applying a sinusoidal load about the mean load at a frequency of 4 Hz and a stress ratio of 0.1. This is the ratio of the minimum stress to the maximum stress experienced during cyclic loading. Strains were measured using an Imetrum video gauge system with a 25mm lens and a nominal gauge length of 125 mm for un-notched samples and 64mm nominal gauge length for the open-hole samples.

3 RESULTS AND DISCUSSIONS

Typical nominal stress-strain results for the investigated un-notched and open-hole configurations are shown in Figure 5. Table 3 summarizes some calculated values for the hybrid configurations. Fibre fracture in the carbon layers was the first observed failure mode for the investigated hybrid configurations. A desired pseudo-ductile tensile stress–strain response with a linear initial part, a wide plateau and a second linear part was observed for the un-notched samples, however the open-hole samples failed suddenly slightly earlier than the pseudo-yield stress point. Local subcritical damage before the failure, i.e. dispersed delamination and fragmentation around the hole tips, resulted in notch insensitivity in the quasi-static tensile loading. It was observed that these subcritical damage mechanisms happen much earlier than the final failure, initiated when the stress reaches the pseudo-yield stress at the hole edge [7], see Figure 5.

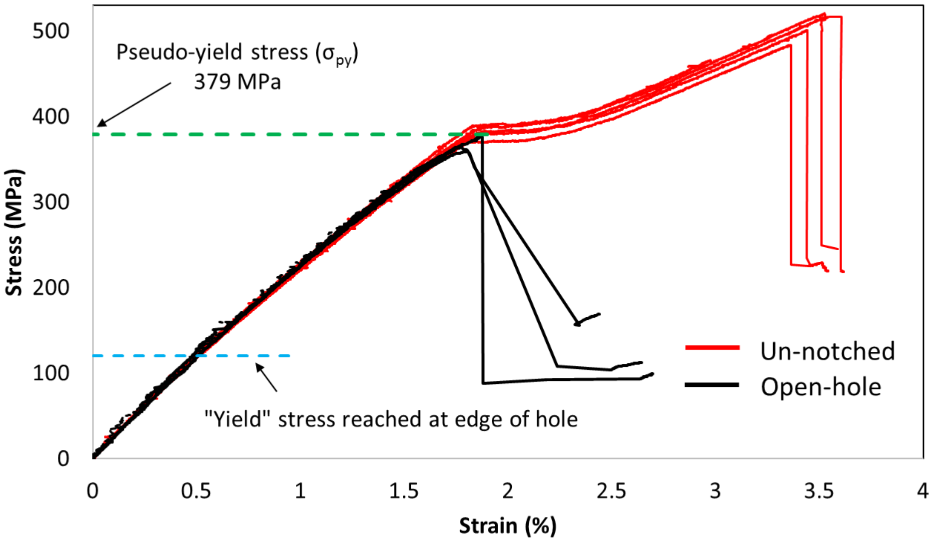

Figure 5. Schematic of the stress–strain graph of a thin-ply hybrid with Pseudo-ductility.

Table 3: Summary of the test results for the un-notched hybrid specimens.

Specimen type	Pseudo-yield strain (%)	Pseudo-yield stress (σ_{py}) (MPa)	Final failure strain (%)	Final failure stress (MPa)	Initial modulus (GPa)
Un-notched	1.80±0.02	379±6	3.5±0.10	504±18	25.1±0.1
Open-hole	1.75±0.06	368±6	1.8±0.06	368±6	25.1±0.1

As can be seen from Table 3, the average σ_{py} is slightly lower for the open-hole laminates, however for the fatigue tests, both the un-notched and open-hole configuration loads are calculated as a proportion of the un-notched σ_{py}. Typical pictures taken from the surface of the fatigued samples are illustrated in Figures 6 and 7. The fatigue tests were interrupted at various stages and the stiffness was recorded. The measured stiffness results at different numbers of cycles are shown in Figure 8. For the un-notched samples cycled at a stress level of 80% of the un-notched σ_{py}, there is a small stiffness reduction from the early cycles caused by matrix cracking, recognizable by the striped pattern on the sample's surface shown in Figure 6. However there is little stiffness reduction up to 100,000 cycles. By increasing the stress level to 90% of the σ_{py}, there is a gradual stiffness reduction due to the appearance of fragmentation and delamination, which leads to final failure of the un-notched samples after 10,000 cycles. A similar behavior was observed for the open-hole laminates, where initially matrix cracking and some slight stiffness reduction were observed for the low stress level (50% of the σ_{py}), up to 100,000 cycles. However a gradual delamination growth was observed for the high stress level (70% of the σ_{py}), which lead to final failure after 30,000 cycles. Near the final failure, the laminate loses all the carbon ply and the angle ply glass contributions, so the final stiffness is just due to the remaining 0 degree glass plies. As can be seen from Figures 7 and 8, due to the translucent nature of the glass layers, the investigated hybrids have the advantage of allowing monitoring of the damage evolution with the naked eye. This can be very useful for inspection purposes, as the damage can be detected visually on the surface or around the notches before any catastrophic failure.

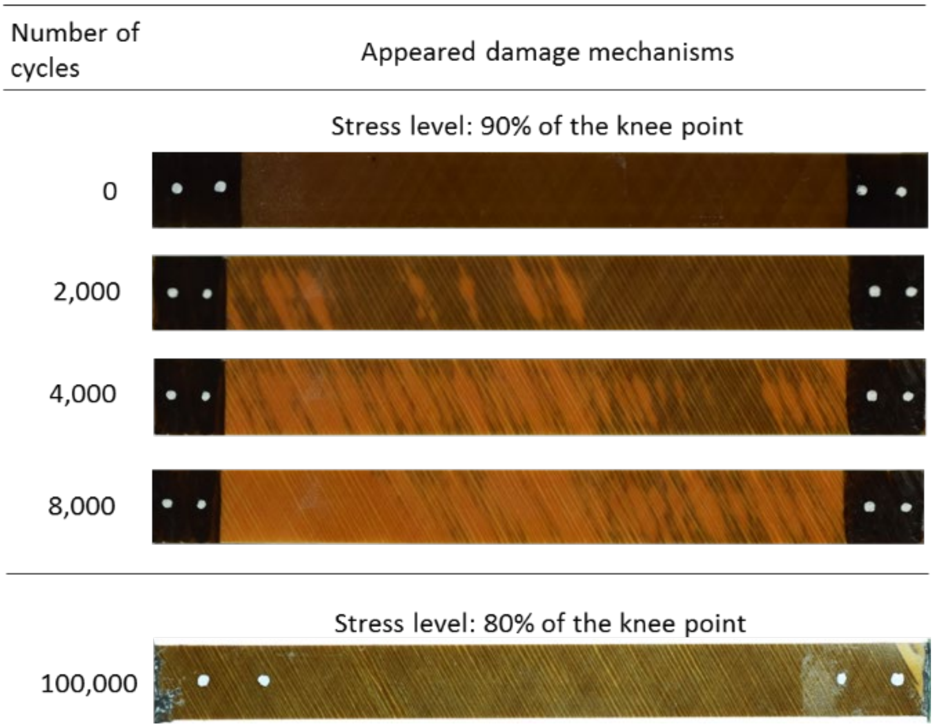

Figure 6. Typical fatigue damage development for the un-notched QI hybrid composites at two different stress levels of 80% and 90% of the un-notched σpy.

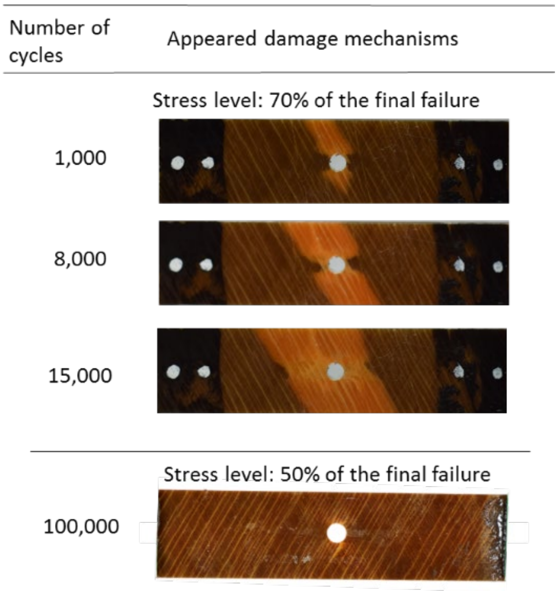

Figure 7. Typical fatigue damage development for the open-hole QI hybrid composites at two different stress levels of 50% and 70% of the un-notched σpy.

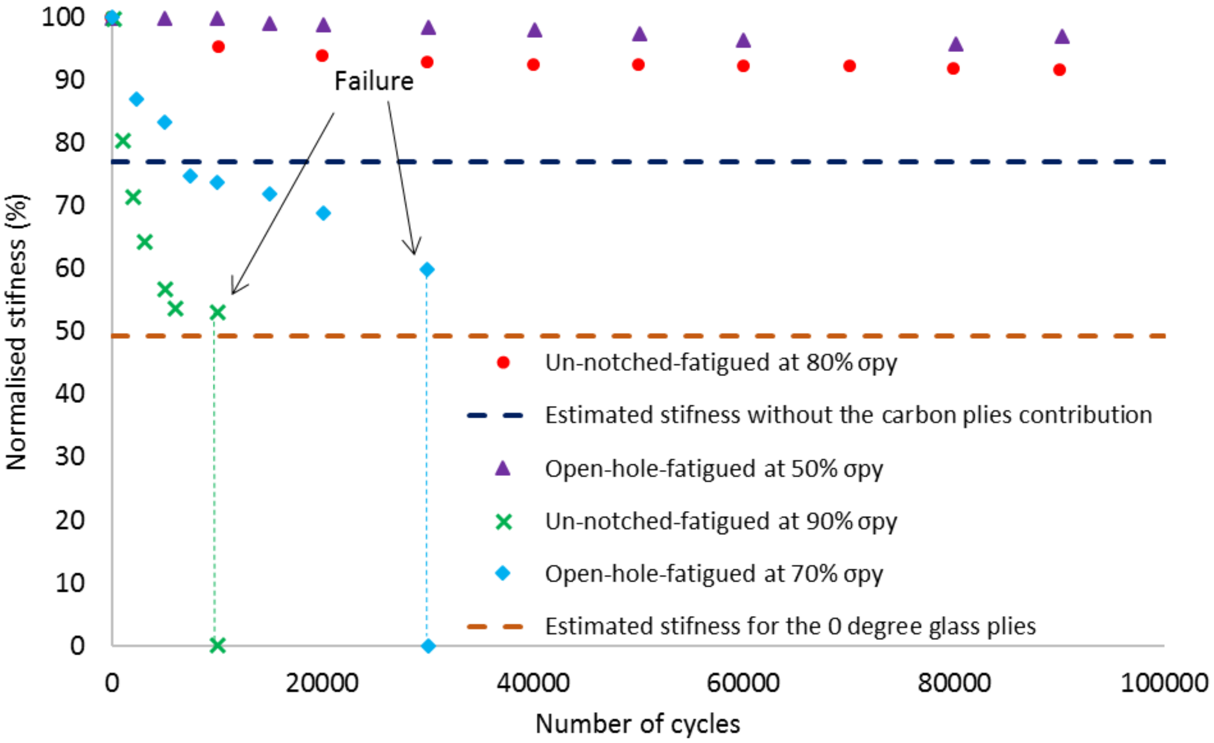

Figure 8. Stiffness loss comparison for the fatigued samples.

4 CONCLUSIONS

This paper has presented the mechanical properties of un-notched and open-hole multi-directional thin-ply hybrid composites subjected to static and cyclic tensile loads. The effect of different loading conditions was examined. The following was concluded:

1. A successful pseudo-ductile un-notched behaviour which also showed notch-insensitivity was achieved through subcritical pseudo-ductile damage mechanisms, i.e. fragmentation and dispersed delamination.
2. For the un-notched samples cycled at 80% of the un-notched σ_{py}, there is a small stiffness reduction from the early cycles caused by matrix cracking, recognizable by the striped pattern on the sample's surface. However the stiffness reduction is small even after 100,000 cycles. By increasing the stress level to 90% of the un-notched σ_{py}, there is a gradual stiffness reduction due to the appearance of fragmentation and delamination with increasing number of cycles. The samples failed after around 10,000 cycles.
3. For the open-hole laminates, a small stiffness reduction caused by some matrix cracking was observed for the low stress level (50% of the σ_{py}), however a gradual delamination growth was observed for the high stress level (70% of the σ_{py}) with increasing number of cycles, which resulted in failure after around 30,000 cycles. The 50% stress level is well above the stress level to induce local subcritical damage at the edge of the hole, which is not visible at low strain levels, reflecting the insensitivity of fatigue performance to the existence of the sub-critical damage.
4. Due to the translucent nature of the glass layers, the investigated hybrids have the advantage of allowing monitoring of the damage evolution with the naked eye. This can be very useful for inspection purposes, as the damage can be detected visually on the surface or around the notches before any catastrophic failure.
5. Overall good fatigue performance of pseudo-ductile hybrid composites, with gradual fatigue damage growth was observed, that shows their applicability for industrial applications.

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