FATIGUE BEHAVIOUR OF PSEUDO-DUCTILE THIN PLY HYBRID COMPOSITES

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ABSTRACT

The fatigue behavior of unidirectional interlayer hybrid composites consisting of thin ply TC35 carbon/epoxy and S-glass/epoxy prepregs has been studied by looking at the fatigue threshold and delamination growth rate before and after the stress level at which fragmentation of the carbon ply initiates. For the pristine specimens, without any fragmentation, there is no stiffness reduction up until 74,000 cycles when fatigued at 90% of the fragmentation initiation stress level.

For the specimens initially overloaded beyond the fragmentation stress level, they can withstand several thousand cycles at high amplitude loads with only a gradual increase in the damage. In these specimens, the stiffness reduction rate depends on the maximum fatigue stress level. At 90% of the fragmentation initiation stress level, the stiffness reduction rate is faster compared to 80 %. This is due to the higher cyclic strain energy release rate at the 90% compared with the 80%. A correlation between the stiffness reduction rate and the damage growth rate over the course of cyclic loading is presented, highlighting the effect of different maximum fatigue loading levels.

1. INTRODUCTION

The low density coupled with high stiffness and strength of advanced polymeric matrix composites makes them an attractive choice of material for structural applications (e.g., wind turbine blades and fuselages) where weight saving and durability is a major concern. However, the limitation of this material is the inherent brittleness, where the failure mode is usually catastrophic without significant damage or warning before failure and little residual load carrying capacity. This renders them unsuitable for a wide range of applications which have unpredictable loading conditions. Usually a much larger safety margin is applied for composites, compared to their metal counterparts. For example, in cyclic loading conditions, the maximum allowable design strain can be an order of magnitude lower than the strain to failure of carbon fibre composites.

To overcome this problem, a new generation of high performance composites with pseudo-ductile or ductile behaviour is needed. Hybridization is one of the basic strategies to create pseudo-ductility, which can alter the failure mode of conventional fibre composites towards a more gradual and progressive failure. Incorporating thin carbon prepreg plies in an interlayer hybrid composite has proven to suppress overall delamination along the specimen length in static tensile loading [1] and produce stable fragmentation, therefore avoiding catastrophic failure. Dispersed ply composites made of thin unidirectional (UD) carbon prepregs have shown superior fatigue properties compared to those with thick blocks of grouped plies through their ability to suppress matrix microcracking, delamination and splitting [2].

A UD interlayer hybrid composite material, comprising thin ply TC35 carbon/epoxy and S-glass/epoxy prepregs, exhibits a pseudo-ductile stress-strain response through fragmentation and stable pull-out of the carbon layer [3]. To assure stable delamination of the central carbon layers after fragmentation, the energy release rate (G_{II}) at the expected failure strain of the carbon layers must be lower than the mode II fracture toughness (G_{IIc}) [1][3].

There are two possibilities that will occur during the service life of a structure made of thin ply hybrid composites. Firstly, it may be fatigued below the fragmentation load level that corresponds with the knee point stress (σ_k) (Figure 2). σ_k is determined at the intersection of the lines fitted through the initial linear and the plateau parts of the individual stress-strain curves as shown in Figure 2. This stress level is chosen for consistency of the evaluation. The second scenario is when the material is overloaded beyond σ_k and it is subject to further cyclic loading below σ_k. For the first case, there may be a fatigue threshold where damage will not occur and this threshold would be very useful for design purposes. For the second case, it is crucial to characterize the rate of damage development during cyclic loading. This will enable the prediction of the material's residual service life and to predict long time behaviour.

The aim of this paper is to study the fatigue behaviour of the UD thin ply hybrid composites that show pseudo-ductile behaviour [3], in two loading conditions, before and after the fragmentation initiation load level.

2. EXPERIMENTAL

2.1. Materials

The materials considered for design, and used in the experimental part of the study were S-Glass/ epoxy prepreg supplied by Hexcel and SkyFlex USN 020 carbon/epoxy prepreg from SK Chemicals. The carbon/epoxy prepreg are made with TC35 carbon fibre. Material data of the fibres and prepreg systems can be found in Table 1. and Table 2.

Engineering Constant	Unit	TC35 Carbon	S-Glass
Elastic modulus	[GPa]	240	88
Failure strain	[%]	1.67	5.50[a]
Tensile strength	[GPa]	4.0	4.8
Density	[g/cm^3]	1.80	2.45
Manufacturer		Formosa	Owens Corning

Table 1. Fibre properties of the applied UD prepregs (based on manufacturer's data)
[a] Measured on single fibre tests

Engineering Constant	Unit	Prepreg Material	
		TC35/epoxy	S-Glass/epoxy
Elastic modulus	[GPa]	114.3[a]	45.7[a]
Failure strain	[%]	1.97[b]	3.98 [5]
Volume fraction	[%]	46.9[a]	50[a]
Cured ply thickness	[mm]	0.023[a]	0.155[a]
Fibre mass per unit area	[g/m^2]	20[c]	190[c]

[a] Calculated based on manufacturer's data
[b] Measured on [SG/C_2/SG] UD interlayer hybrid in static tension
[c] Based on manufacturer's data

Table 2. Cured ply properties of the applied UD prepregs

The failure strain for TC35/epoxy is an average of 5 measurements and it is defined as the first carbon ply crack visible in the specimen.

2.2. Manufacturing

UD laminates consisting of thin carbon and standard thickness glass prepregs were laid up on top of a flat aluminium plate in the following sequence [SG/C_2/SG], where SG stands for S-glass plies and C for carbon plies. Both prepreg systems have similar cure temperatures and were found to be compatible. The laminates were cured in an autoclave at the recommended cure temperature and pressure cycle for Hexcel 913 epoxy resin (60 min@125 °C, 0.7 MPa). A diamond cutting wheel was used to cut the specimens. To protect the specimens from the high clamping force and avoid premature failure in the grip region, end tabs with 1.6 mm thickness, made of glass/epoxy cross-ply plates, were bonded to the specimens using a two-part epoxy adhesive and cured for 60 min@70 ºC.

2.3. Specimen Geometry

The geometric parameters are shown on the side and top view schematics of the sandwich type thin ply hybrid composite specimens in Figure 1. Nominal specimen dimensions were 240/160/20/0.357 mm-overall length (L)/gauge length (L_f)/ width (W)/ thickness (h) respectively.

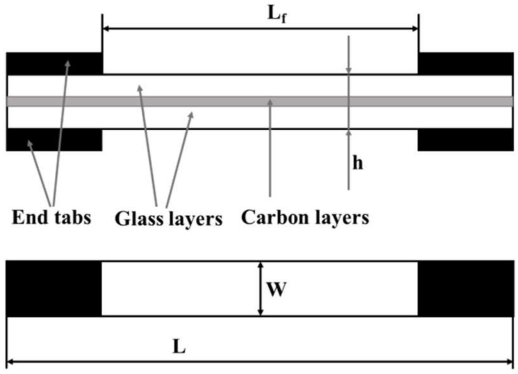


Figure 1. Schematic of [SG/C_2/SG] sandwich type configuration.

For the particular specimen configuration used in this experiment, the nominal carbon/glass thickness ratio is 14.8%.

2.4. Test Procedure

Static tension and tension-tension fatigue tests were performed on the UD interlayer thin ply hybrid laminates on a computer controlled Instron type 25 kN rated universal hydraulic test machine with wedge type hydraulic grips. For the static tests, the hybrid specimens were loaded in uniaxial tension and displacement control using a crosshead speed of 2 mm/min. Five specimens were tested in static tension to determine the fragmentation initiation stress level (σ_k) as shown in Figure 2. The pristine specimens were fatigued at three different stress levels below σ_k (90%, 87%, 80%). In order to pre-fracture the other specimens, uniaxial static tensile loading was performed on the specimens under displacement control using a crosshead speed of 0.5 mm/min. The tests were stopped when at least one fragmentation crack in the carbon layer had developed across the width of the specimen. They were then fatigued at two load levels (90% and 80% of σ_k). Both fatigue tests were conducted under load control by applying a sinusoidal load about the mean load at a frequency of 2 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 nominal gauge length of 130 mm. Overall videos were recorded at increasing numbers of cycles by the video gauge camera and the damage growth area was evaluated using ImageJ software.

3. RESULTS and DISCUSSIONS

3.1. Static tension behaviour of UD thin ply hybrid laminates

A typical stress-strain curve response of the UD interlayer thin ply hybrid laminates under static tension is shown in Figure 2. Please note, that the following explanation of static tension damage mechanisms is for the particular specimen in Figure 2. To determine the first carbon layer fracture, a video taken from this specimen with the strain measurement system was visually studied. The corresponding first carbon layer fracture for this specimen is at 2.13% strain. It was possible to detect the carbon layer cracks because of the associated delamination surrounding the cracks and the translucent nature of the glass plies revealing the delaminated. At the knee point stress (σ_k), a process of multiple carbon layer fragmentation has been established [6] with a plateau on the stress-strain curve. Starting from 2.16 % strain, which is the knee point strain (ε_k), multiple distributed cracks appeared in the carbon ply. During further loading, the localized delaminations grow stably until they are almost completely joined together with the fragmentation reaching saturation at 2.78% strain. After this point, the stress rises further until 3.5% strain. The inset in Figure 2 displays a specimen after the test has been interrupted at 3.5 % strain, at which point it has localized delaminations surrounding the carbon ply cracks.

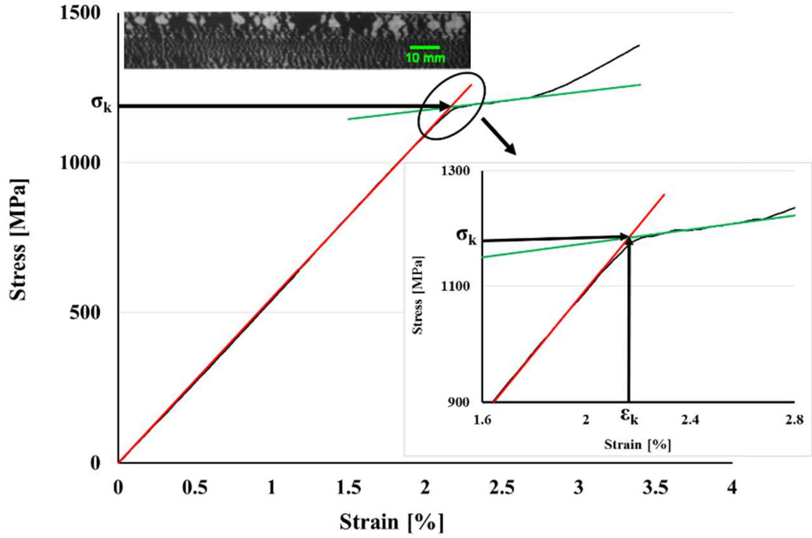


Figure 2. Typical stress-strain response of [SG /C_2/SG] configuration displaying σ_k and ε_k as the knee point stress and strain determined from the intersection of initial linear and plateau lines, and damage state at end of loading.

For [SG/C_2/SG] thin ply hybrid configuration, the average knee point stress (σ_k) and strain (ε_k) from five specimens tested in static tension are 1048 MPa and 2.03% respectively.

3.2. Fatigue behaviour of the pristine UD thin ply hybrid laminates

From the fatigue experiment on pristine thin ply hybrid laminates, it is shown that there is negligible stiffness reduction up until 74000 cycles even at maximum 90 % of σ_k. The summary of this testing is shown in Table 4 for three different maximum loading levels. Please note that the maximum loading level is calculated from the average knee point stress (σ_k).

Specimen	Maximum loading level	Number of cycles [N_f]	Stiffness reduction
1	90 % σ_k	74000	
2	87 % σ_k	74000	Negligible
3	80 % σ_k	74000	

Table 4. Fatigue test results for pristine [SG /C_2/SG] configuration

3.3. Fatigue behaviour of overloaded UD thin ply hybrid laminates

The overloaded specimens were fatigued at two different maximum stresses, 80% and 90% of σ_k. For the specimen fatigued at 80% σ_k , initially it was overloaded until 2.40% strain under static tension and from the video taken from this specimen, the first carbon layer fracture occurred at 2.11% strain. At the beginning, the fracture appears as small patches growing steadily across the width of the specimen.

The loading was then terminated when the distributed carbon fracture had extended across the full width. For the 90 % σ_k fatigued specimen, the overloaded final strain point was 2.37 %. For this specimen, the first carbon fracture appeared at 2.16% strain but with large delamination patches at the final strain point as shown in Figure 6. Stiffness reduction was measured at different numbers of cycles to monitor damage growth of the pre-fractured specimens. A plot of stiffness reduction versus the number of cycles for 80% and 90% of σ_k is shown in Figure 3.

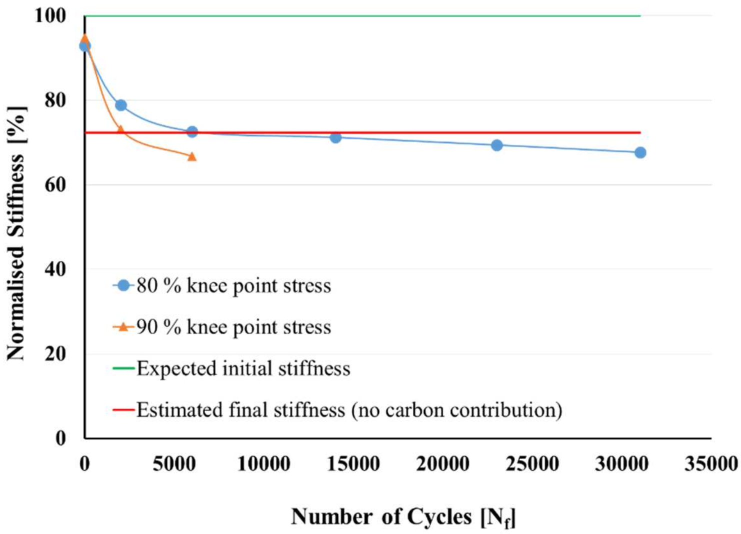


Figure 3. Typical stiffness reduction with increasing number of cycles at 80 % σ_k and 90 % σ_k for [SG /C_2/SG] configuration.

After the specimens were overloaded, the reduction in normalised stiffness due to the initial fragmentations was quite similar, i.e. 7 % and 5 %. These specimens were subsequently cycled at 80 % σ_k and 90 % σ_k respectively. For both load levels, the final normalized stiffnesses are well below the estimated final stiffness without the carbon ply contribution. The reason behind this is probably that a small amount of damage was detected in the glass ply layers, in the form of glass/epoxy layer splitting, which could cause further stiffness reduction for both specimens. It is clearly shown in Figure 3 that the stiffness reduction rate for 90 % σ_k is higher compared to 80 % σ_k. There is a quadratic relation between energy and stress (energy is proportioned to stress squared). As a consequence, the delamination growth rate is higher for the 90 % σ_k and in turn there is a higher stiffness reduction rate. Figure 4 depicts damage growth of a typical UD thin ply hybrid laminate at different numbers of cycles at the maximum fatigue loading of 80 % σ_k.

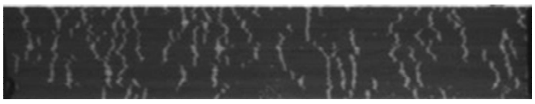
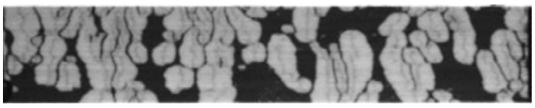
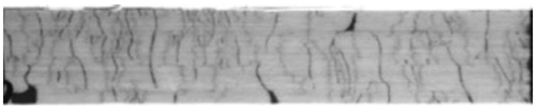
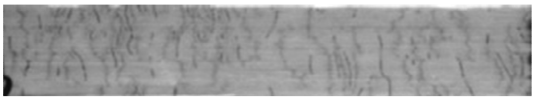
Number of Cycles [N_f]	Damage Mechanisms
0	
2000	
6000	
14000	
23000	
31000	

Figure 4. Typical damage mechanisms [SG /C_2/SG] configuration at maximum fatigue loading of 80 % σ_k.

From Figure 4, it is shown that initially the fragmentation is staggered across the specimen with at least one continuous crack across the full width. During the initial 2000 cycles loading, delamination surrounding the cracks grew stably until they were joined together by the adjacent delaminated area. From 2000 cycles until 6000 cycles, the delaminated area extended over almost the entire specimen. From the 14000 cycles until 31000 cycles, there was no further delamination growth observed but before 15000 cycles, damage in the form of fibre splitting occurred in the glass layers. Please note that the number of cycles in Figure 4 is correlated with Figure 5.

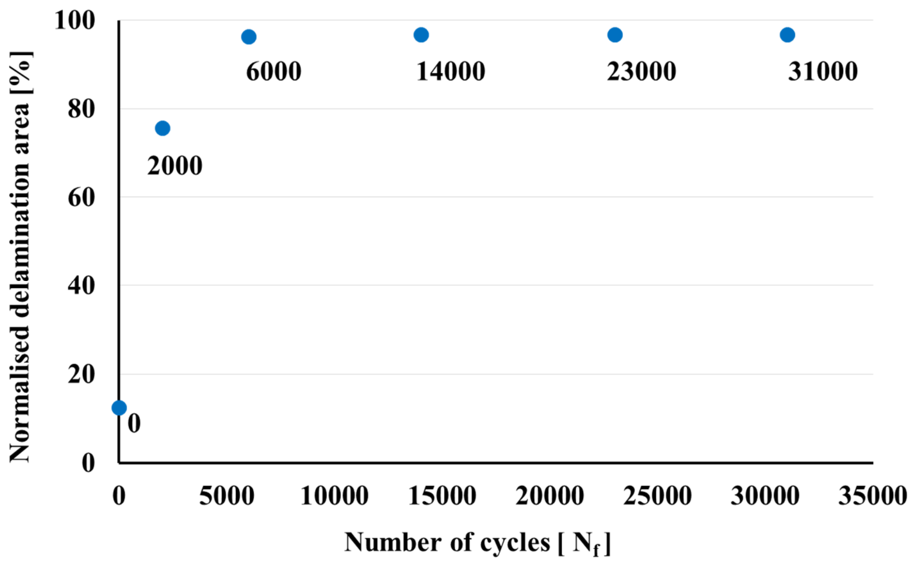


Figure 5. Typical delamination growth area with increasing number of cycles at 80 % σ_k for overloaded [SG /C_2/SG] configuration.

It is shown in Figure 5 and Figure 7, that for a typical overloaded UD thin ply hybrid fatigued at 90 % σ_k, the delaminated area grows stably from 0 cycles until 2000 cycles, with no further change up to 6000 cycles. For the 80 % σ_k case, delamination grows up until 6000 cycles and then from 6000 cycles until 31000 cycles there is a plateau which corresponds to no delamination growth.
Figure 6 depicts damage growth of the UD thin ply hybrid laminate at different numbers of cycles at a maximum fatigue loading of 90 % σ_k.

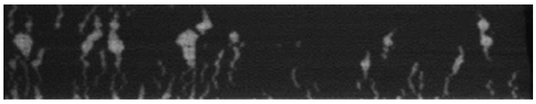
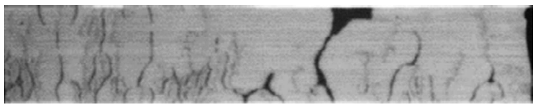
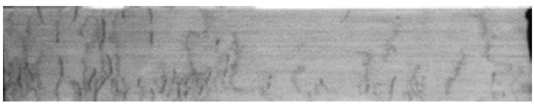
Number of Cycles [N_f]	Damage Mechanisms
0	
2000	
6000	

Figure 6. Typical damage mechanisms for overloaded [SG /C_2/SG] configuration at maximum fatigue loading of 90 % σ_k.

From Figure 6, it is shown that there are large patches of delamination from the fragmentation extending across the width of the specimen. From 0 cycle to 2000 cycles, delamination grows stably from the large patches to join up with the adjacent delaminated areas. At 6000 cycles, the delaminated area has covered almost the entire specimen. Between 2000 cycles and 6000 cycles, damage in the form of glass/epoxy layer splitting appears in the glass layers. Please note that the number of cycles in Figure 6 is correlated with Figure 7.

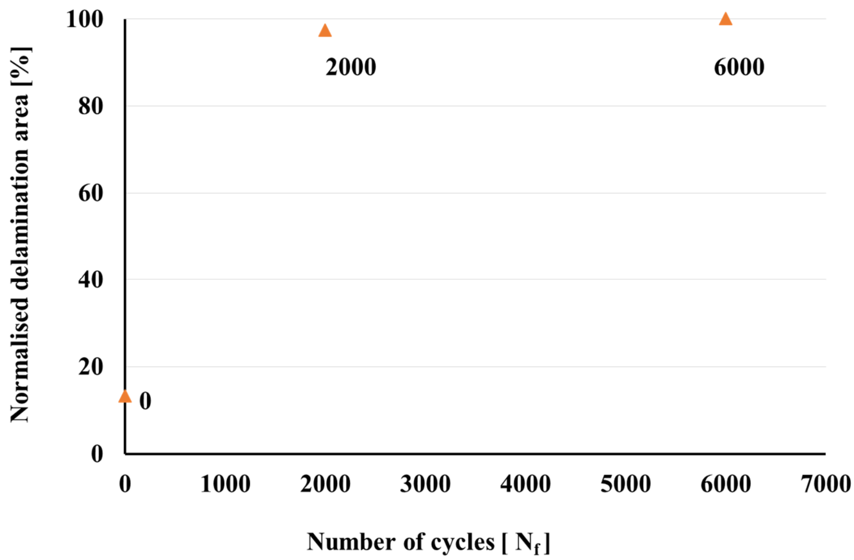


Figure 7. Delamination area growth with increasing number of cycles at 90 % σ_k for [SG /C_2/SG] configuration.

4. CONCLUSIONS

The behaviour of UD thin ply hybrid composites under cyclic loading has been studied by looking at the fatigue behaviour of pristine specimens cycled at 90 %, 87 %, and 80 % of the knee point stress $\sigma_{k,}$. Up until 74000 cycles, there is negligible stiffness reduction even for the 90% σ_k.

The overloaded specimens show a gradual increase in delamination area. At 90 % $\sigma_{k,}$ the stiffness reduction rate is faster compared to 80 % $\sigma_{k.}$ This is due to the higher strain energy release rate for the former. Higher stiffness reduction rate also means higher delamination growth rate. In general, the overloaded specimens are able to withstand cyclic loading at high amplitude with only a gradual increase in damage over thousands of cycles.

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