DAMAGE EVOLUTION UNDER BENDING FATIGUE IN CROSS-PLY COMPOSITE LAMINATES

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Abstract

Low cycle fatigue tests (0.5 Hz) in 4-point bending were conducted to study the damage evolution in carbon/epoxy cross-ply laminates. Damage development in the form of matrix (resin) cracking was recorded at different stages of the testing by means of the replica tape technique. The resulting changes in the flexural stiffness are plotted against the amount of damage and number of cycles. Microscopic observation of the replicas revealed matrix cracking at average ply strains of around 0.3% during the first few loading cycles. Matrix cracks are formed from disperse fibre/matrix debonds in the off-axis plies, which eventually coalesce to form a macro-crack. Those matrix cracks were found to grow gradually in size and number in different plies as cycling increased. The effect of matrix cracking initiation and growth on the stiffness of the laminate is found to be less marked than in pure tensile loading, but can still lead to delaminations and ultimately fibre failures. Changes in the flexural stiffness are compared to measured data from reverse bending fatigue tests.

1 Introduction

In the last few years, fibre reinforced composites have become an important material type for structural applications. This is in part due to the enhanced mechanical performance exhibited by composites when compared to most common metals. However, as in metals, the mechanical response of composites is affected by the initiation and growth of damage [1-3].

Damage development in composites is characterised by the initiation and growth of different mechanisms, sometimes interacting. Under tensile loading, damage starts with matrix cracking in the off-axis plies of a laminate [4, 5]. While this mechanism usually does not represent high danger for the structure [6], it certainly affects the stiffness and strength of the composite laminate [7], and also induces inter-ply cracking (delamination), which can be more detrimental [8, 9]. Under compressive loads, fibre micro-buckling and kinking have been observed [10, 11]. In this case damage affects directly the load bearing plies and propagates rapidly, resulting in catastrophic failure [11].

In structural components, however, rather than pure tensile or compressive loading a combination of both is usually found. In the case of bending, the way in which the load is distributed affects differently the development of damage in different plies. As a result, evolution of damage under flexural loads is different through the thickness of the laminate, affecting differently its mechanical response when compared to pure tension or pure compression conditions.

In this work, 4-point bend loading was used to induce and study damage development in different plies of carbon-epoxy cross-ply specimens under low cycle fatigue. The damage generated in the edge of the specimen was recorded in acetate tapes by using the replica tape technique. Using the optical microscope the different tapes were analysed and the damage in the form of transverse cracks was compared at different stages and conditions of the tests. It is found that in bending, transverse cracks develop in a more gradual fashion, contrasting to the way displayed in pure tension. In addition, the effect of the initiation and development of transverse cracks is observed to affect very little the flexural stiffness of the tested specimens.

2 Materials and specimen preparation

Carbon-epoxy Cycom 12K HTS40/997-2 unidirectional pre-preg tape was used to prepare a 16-ply $(0/90)_{4s}$ laminate. The laminate was cured in an autoclave at 177°C following the manufacturer's recommended cure cycle, resulting in an average thickness of 4.26mm. The specimens were cut to a final size of 250x25mm. After cutting, one edge in each specimen was ground and subsequently polished to allow for the observation and recording of damage by using the replica tape technique. Electrical resistance strain gauges were attached to both surfaces of the specimen to monitor the longitudinal strains in the tensile and in the compressive side. The unidirectional pre-preg tape properties corresponding to a fibre volume fraction $V_f=0.65$ are summarised in table 1 using data from the material manufacturer.

Material	E_{11} (GPa)	E_{22} (GPa)	G_{12} (GPa)	ν_{12}
Pre-preg HTS40/997-2	156.5	9.8	5.2	0.3

Table 1. Summary of the elastic properties for the unidirectional pre-preg.

3 Mechanical testing

The tests were performed in a servo electric universal testing machine conditioned with a fixture to apply simple bending, Figure 1. Strain, load, and displacement data were collected by using a DAQ NI USB-6008 acquisition card together with a Lab View program. To obtain a figure of the maximum load and strain one specimen (S6) was tested to fracture at a rate of 0.5mm/min, under quasi-static 4-point bend loading. Although the load was applied until complete fracture, the test was interrupted at different stages (without removing the test piece) to apply replica tapes to monitor and record the damage in the polished edge of the specimen. To obtain each replica the test had to be stopped for around 20 minutes, after which time the test was resumed normally.

Figure 1. Servo-electric universal machine used in the tests and specimen instrumented and mounted.

Other specimens (S7-S10) were tested in fatigue with a frequency of 0.5Hz. For testing, the specimen in turn was initially loaded up to a previously defined mean value. The cyclic load was then applied around predefined limits. In specimen S10 the cyclic load was applied alternately in both sides to emulate reverse bending. For this, the cyclic load was applied normally, and every 1000 cycles the specimen was turned up and the loading was continued. Table 2 shows the test conditions for each sample.

At the beginning of each fatigue test, and after certain number of cycles, the test was interrupted to load the specimen quasi-statically. This was to obtain comparative values of the flexural stiffness variation during the different stages of testing, which was compared by plotting the applied moment versus the angle of rotation at the ends of the specimen. In these quasi-static tests, the loading rate was set to 2mm/min and the specimen was loaded up to the mean value used in the fatigue tests. Replica tapes recording the damage were also taken when the tests were interrupted.

Specimen	Main loading type	Load range (kN)	Rate for quasi-static loading	Maximum number of cycles
S6	Quasi-static	0 - 3.35 (breakage)	0.5 mm/min	-
S7	Fatigue	1.35 - 2.05	2 mm/min	50000
S8	Fatigue	1.67 - 2.55	2 mm/min	50000
S9	Fatigue	1.86 - 3.10	2 mm/min	4670
S10	Fatigue	1.50 - 2.50 (Reversed)	2 mm/min	7000

Table 2. Summary of the test conditions for each specimen.

The replicas of each specimen’s edge at different stages of the tests were taken to the optical microscope and the formed cracks were counted along the specimen gauge length. The amount of damage was established by estimating the crack density in the 90º off-axis plies of the specimen.

4 Results

Analysis of the replicas in the optical microscope showed that transverse cracking started early during the testing in all the specimens. Cracking was observed at averaged ply strains in the order of 0.3%. Nevertheless, the length of those initial cracks rarely surpassed a few fibre diameters along the thickness of the transverse ply.
The increasing on the load or the number of cycles resulted in a crack multiplication process and also in the extension of some of the previously formed cracks. Although the initially small cracks can form very close to each other, the growth of one of them inhibited the development of the neighbouring ones. As a result, the crack density in the ply was observed to tend to a limiting value. Such value, nevertheless, was different for different loading conditions.

4.1 4-point Quasi-static bending loading

In the specimen tested quasi-statically to fracture (S6), matrix cracks were firstly observed in a replica at an average ply strain of 0.32%. In this test, the application of load was interrupted at different stages to apply the replicas and record damage. The test was interrupted at 0.55, 1.58, 2.28 and 3.20kN. Correspondent measured outside longitudinal strains are 0.40%, 0.58%, 0.80%, and 1.15%. The specimen fractured when the load reached 3.35kN, at a surface longitudinal tensile strain of 1.26%.
As the load was increased the crack density and the length of some cracks also increased. Figure 2 shows the trends of the variation of crack density as a function of the strain for different 90º plies. Figure 2a considers cracks of more than half ply in length. On the other hand, if smaller cracks are considered, the tendency is shown in Figure 2b.

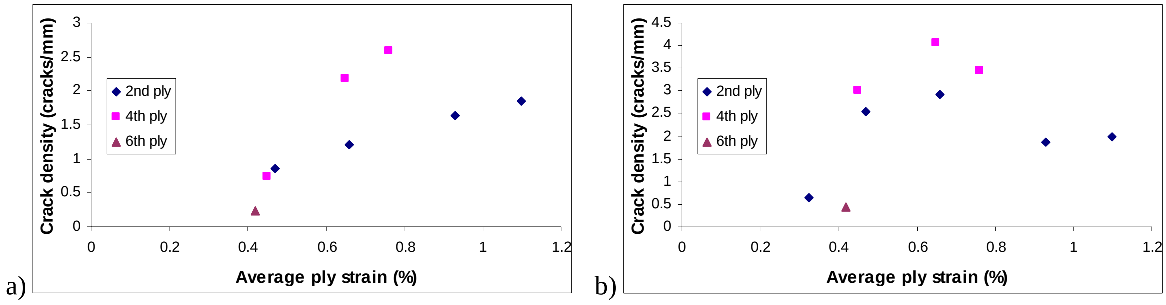


Figure 2. Crack density variation at different strains and different 90º plies. a) Considering large cracks; b) considering all cracks.

Analysis of the fractured specimen showed delamination in different layers in addition to transverse cracks. The initiation and growth of transverse cracks seems to have little effect on the flexural stiffness of the specimen, as suggested by Figure 3, where the applied bending moment is plotted against the angle of rotation at one end of the specimen.

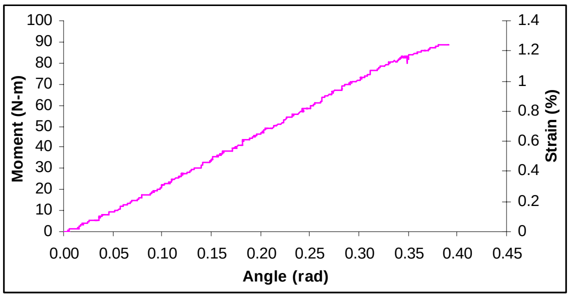


Figure 3. Variation of the applied moment and strain versus the angle of rotation on the specimen S6.

Although delamination was observed in a replica taken at a measured surface strain of 1.15%, which corresponds to a notorious change in the slope in Figure 3, such change seems to be more related to the damage suffered by the specimen at the zones where the load was applied, Figure 4. The final failure of the specimen is then consequence of the propagation of the damage at the already mentioned zones.

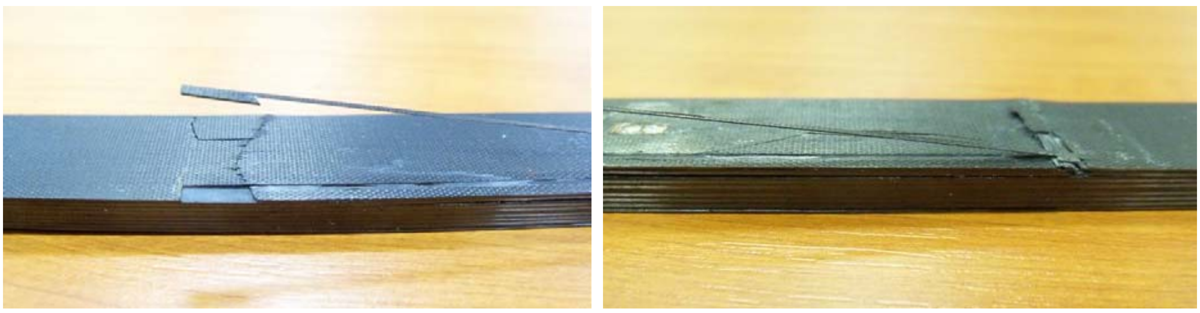
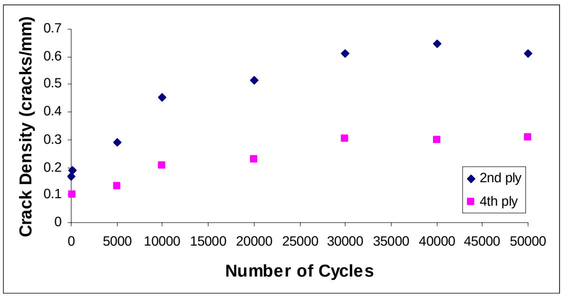


Figure 4. Damage initiated at the loading points and run along the specimen. Final failure of specimen S6.

4.2 4-point Fatigue bend loading

For the specimens loaded in fatigue, transverse cracking also appeared at early stages of the testing. Specimen S7 was firstly loaded quasi-statically up to 1.67kN (0.6% strain) at a rate of 2mm/min. After the replica was taken, cyclic loads were applied between 1.35kN - 2.05kN. When reaching a certain number of cycles, the test was interrupted to obtain more replicas and to load the specimen quasi-statically to obtain a figure of its flexural stiffness. Crack density as a function of the number of cycles is plotted in Figure 5.

a) 

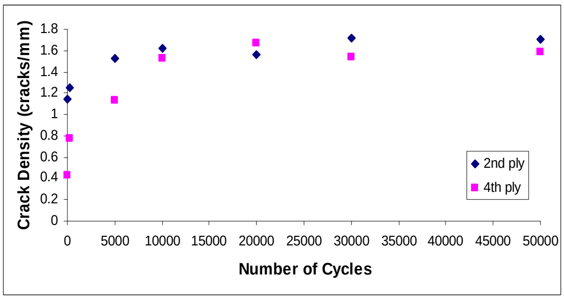
b) 

Figure 5. Crack density variation as cycling increased. a) specimen S7; b) specimen S8.

The specimen S8 was also loaded quasi-statically but in three steps: up to 0.95kN, 1.3kN and 2.0kN (0.4%, 0.5% and 0.74% in strain). A replica was taken in each step. The rate of displacement for the application of load was also set to 2mm/min. In this specimen matrix cracking was observed at average ply strains as low as 0.28%. However, although the crack density at such point was considerably low it increased rapidly as the load was augmented.
Similar to S7, after taking replicas at each stage, cyclic loads were applied to specimen S8. In this case, however, the loads fluctuated between 1.6 and 2.6kN, resulting in strains in the order of 0.7% to 0.9%. A plot of the variation in the crack density in S8 is also shown in Figure 5.
Although crack density increases with cycling in both S7 and S8 specimens, the plots suggest that the rate of growth and final crack density depends on the initial state of damage and the magnitude of the loads applied. While in S8 damage was observed to arise during the initial quasi-static loading stages, in S7 the initial damage is considerably lower, even for similar strain values. It is suggested then, that the time during which the load is applied also plays an important role in the generation and growth of cracks.

This effect was also observed in specimens S9 and S10. Although the applied load was similar or higher than the one applied in S8; for S9 and S10 the load was applied in just one stage. In both specimens, the initial crack density was high, but mainly populated by small cracks. Specimen S9 was fractured unexpectedly due to problems with the test machine below 5000 cycles. Nevertheless, one replica was taken just after the initial load, up to 2.5kN. A high amount of small transverse cracks were observed; however, very few of them were larger than half ply thickness. The crack density considering only larger cracks was in the order of 0.25. Contrastingly, if all cracks are considered, the density increases to 2.75 cracks/mm.
In specimen S10 the damage was generated in similar fashion. Small cracks were formed dispersedly all over the damaged ply (loaded in tension) during the initial loading stage. For this specimen the load was also applied quasi-statically up to 2.5kN. However, in this case the load was reduced to 2kN and then cyclic loads were applied ranging from 1.5kN to 2.5kN. The variation in the crack density in S10 for the second and fourth ply in the tensile side is shown in Figure 6.

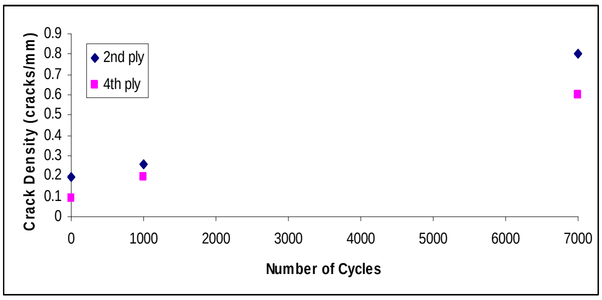
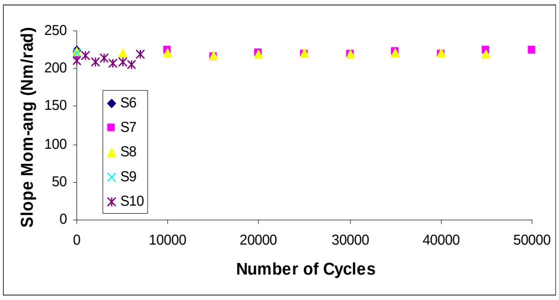


Figure 6. Crack density variation in specimen S10 with the increased cycling.

Regarding to the variation of the flexural stiffness as damage progressed, it can be observed in Figure 7a that transverse cracking initiation and growth has a very little effect. In Figure 7 the slope of the moment-angle is used to assess the flexural stiffness of the specimen, and is plotted against the applied number of cycles.

a) 

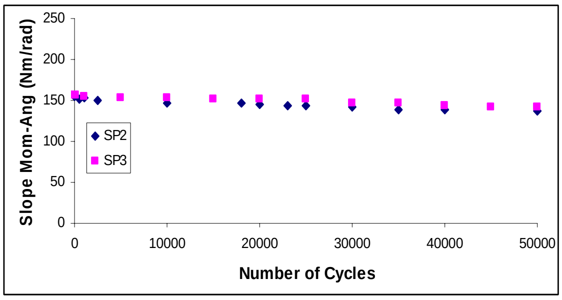
b) 

Figure 7. Variation of the moment-angle against the applied number of cycles. a) Non-reverse 4-point bending; b) reverse bending.

Figure 7b shows data obtained from tests in reverse bending [12]. The difference in the plots is attributed to the introduction of shear stresses in the specimens shown as SP2 and SP3 as a result of the working characteristics of the testing machine. In such specimens, although no damage in the form of transverse cracks apart from the ones arising from voids was reported, it can be observed in Figure 8 the formation of angle cracks, which are assumed to be the result of shear loads.

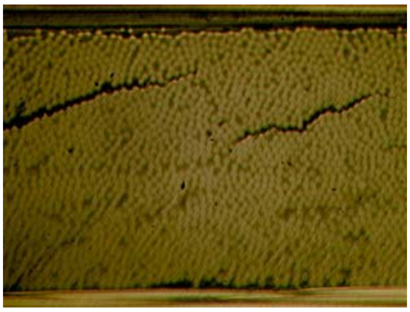


Figure 8. Inclined cracks in a 90º off-axis ply, attributed to shear loading (ply thickness=0.27mm).

5 Conclusions

Damage in the form of transverse cracks can arise early during the loading of a composite structure. Nevertheless, although in pure tensile loading transverse cracking has a marked effect on the mechanical response of the laminate, in bending the flexural stiffness is much less affected, since half of the specimen is loaded in compression and resin cracks are constrained. In the reported tests, rather than arising and growing instantly along the ply thickness, the cracks evolve in a more progressive way. Multiple cracks initiate in the transverse ply, and some of them grow along the fibre/matrix interface as the load or number of cylces is increased. According to the observations in this work it is suggested that not only the initial damage, magnitude of loading, and number of cycles play an important role in the developing of transverse cracks, but also the time for which the loading is applied. However, more attention must be directed to this aspect. It should be said that although these transverse cracks do not affect the flexural modulus, the torsional resistance may be reduced (something that could be examined in near future research) and delaminations can be triggered, which then can reduce the lateral support of the 0 plies and fail prematurely due to fibre microbuckling, a fibre instability failure mode [10, 11].

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