EFFECT OF CARBON NANOTUBES ON FATIGUE LIFE OF CARBON FIBER/EPOXY COMPOSITES

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1 Suppression of damage development

High performance fiber-reinforced polymer composites (FRCs) possess excellent stiffness and strength, but their toughness is limited by early damage initiation. Damage in the form of transverse cracks can jeopardize reliability of composite parts operating under fatigue loading and its retardation in early stages of damage development is desirable. In the previous study [1,2] the authors investigated the effect of carbon nanotubes (CNTs) on the initiation and development of damage in a woven carbon fiber/epoxy composite under quasi-static tensile loading. The composite was produced using resin transfer moulding (RTM) and contains 0.25 wt% of CNTs in the matrix. The study concluded that CNTs have a hindering effect on the formation of transverse cracks. The conclusion was drawn from a combined analysis of the acoustic emission measurements (reporting a pronounced shift of all damage development thresholds towards higher strains, Fig.1) and X-ray/ SEM observations (revealing a lower crack density in the CNT modified composite).

The hindering effect of CNTs on the formation and development of matrix cracks in carbon fiber/epoxy composites may be an important notion for research efforts aiming at improving fatigue life of these materials. In [3] it is suggested that there are possible interrelations between damage initiation and transition thresholds in quasi static tensile tests and limits of tension-tension fatigue life. The argument is supported by data on the static damage initiation thresholds and tension-tension S-N curves for glass/epoxy and carbon/epoxy textile composites with a variety of architectures (plain weave, twill weave, 3D woven, 3D braided, non-crimp fabrics, etc). It is stated that the fatigue limit for carbon fiber composites falls between two thresholds corresponding to the onset of transverse cracks and the appearance of local delaminations, respectively. If the hypothesis about interrelations between transition thresholds in quasi static tensile tests and limits of tension-tension fatigue life is confirmed, then the hindering effect of CNTs on damage initiation and development on the micro-level may have an important role to play in the fatigue properties of these composites. The current work aims to investigate the effect of CNTs on tension-tension fatigue life of woven carbon fiber/epoxy composites with CNTs introduced in the matrix.

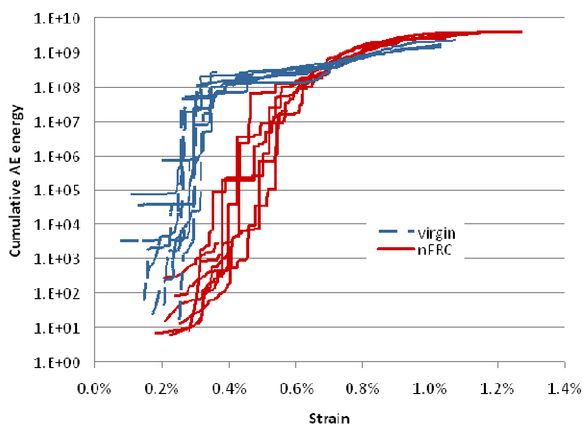

Fig. 1 Cumulative AE energy vs. strain for the virgin composite and nFRC.

2. Composite production

In the present study, woven carbon/epoxy composite plates with and without 0.25 wt% of CNTs in the matrix are produced. The textile reinforcement is a twill 2/2 woven fabric from Hexcel (G0986 injectex, Table 1), the epoxy resin is Epikote 828LVEL and the hardener is Dytek DCH-99. The CNTs were produced by Nanocyl and incorporated in a Bisphenol-A epoxy resin (EpoCyl NC R128-02). The received master batch epoxy resin contained a high content of non-functionalized MWCNTs, with an average diameter around 9 nm and a length of several microns.

Table 1 Twill 2/2 woven carbon fabric

Hexcel G0986 injectex	
Fabric type	Twill 2/2 woven
Areal density, g/m2	300
Fibers	Carbon AS4C
Yarns	6K
Linear density, tex	400
Picks and ends, yarns/cm	3.5

The plates were produced using the resin transfer moulding technique with the processing parameters listed in Table 2.

Table 1 RTM production parameters

RTM parameters	
Number of fabric layers	7
Spacer thickness, mm	2.0
Degassing time, min	20
Applied injection vacuum, mbar	10-20
Injection temperature, °C	40
Injection pressure, bar	2
Curing temperature, °C	70
Curing pressure, bar	4
Curing time, hour	1
Post-curing temperature, °C	150
Post-curing pressure, bar	4
Post-curing pressure time, hour,	1

The thickness variation and the fiber volume fraction V_f of FRCs and nano-engineered fiber reinforced composites (nFRCs) are summarized in Table 3.

Table 3 Thickness and V_f variation

	Thickness, mm	V_f, %
	Average, std	Average, std
FRC	2.14 ±0.044	55.3 ±1.1
nFRC	2.06 ±0.087	57.3 ±2.4

The quality control of the composite cross-sections with optical microscopy confirmed that composites had good impregnation without detected voids or dry areas**.**

3. Fatigue life results

The fatigue tests were performed in a load control mode under constant stress amplitude, assuming the stress ratio R = 0.1 (ratio of the minimum to the maximum stress in the cycle) according to ASTM D3479-36 standard. These tests were carried out both in the fiber and bias directions. The samples failed away from the end tabs (Fig.2).

It is found that the number of cycles till failure for the virgin and nano-engineered composite (nFRC) tested in the fiber direction is about the same for the high stress levels. It is somewhat expected as fatigue properties for low cycle fatigue are dominated by properties of the fibers, and nano-modification of the matrix has a very limited effect. The number of cycles is markedly increased for low stress levels. The reason for this is that the high cycle fatigue behavior is strongly affected by fatigue performance of the resin, and one may expect improvement with nano-modification of the resin. The data for the lowest stress levels are presented in Fig. 3 for the fiber and bias directions. The arrows indicate samples that are not broken.

From the stress-strain curves recorded in the fatigue tests in the bias direction (Fig.4), the data show significant hysteresis in each cycle. The consecutive cycles are also shifted, which indicates a progressing permanent elongation of the sample. It is interesting to note that the FRC sample has a larger start strain in comparison with the strai of the nFRC sample in the same cycle. For example, after 72000 cycles, the start strain of the FRC is more than 0.06, but for the nFRC it is less than 0.01. This means that after the same number of cycles, the FRC has a larger elongation, this was also apperant from the appearance of the failed specimens (Fig. 2).

(a)

(b)

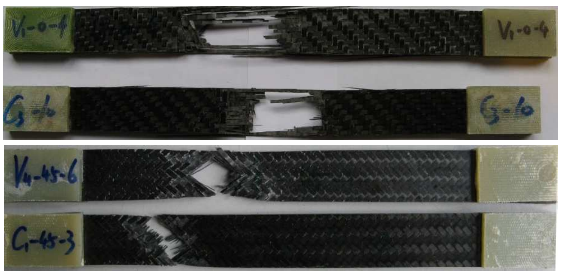

Fig. 2 Fracture surfaces after fatigue tests in the (a) fiber direction and (b) bias direction.

The X-ray radiography and scanning electron microscopy were employed to investigate damage patterns in the tested specimens. These studies indicate a significant decrease in the density of transverse cracks and delaminations in the nano-modified composite even if the latter was subjected to a higher number of cycles (Fig. 5). It is important to note that the number of cycles for the nFRC is about 4 times than that for the FRC. The X-ray study indicates that the crack density in the nFRC is less than that in the FRC. Fig. 6 shows images of samples tested in the bias direction (at 100 MPa).

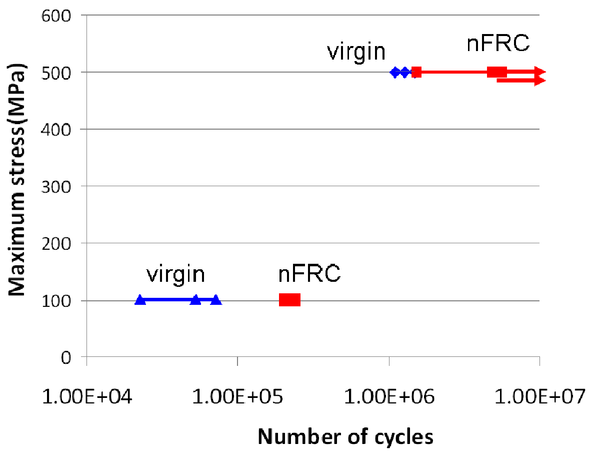

Fig. 3 The tension-tension fatigue data for the virgin (blue) and CNT modified (red) carbon fiber/epoxy composites in the fiber and bias directions, at 500 MPa and 100 MPa load level, respectively.

The dispersion of CNTs in the composites is found to be not homogeneous as shown in Fig. 7. Although the resin has been stirred for 10 minutes during the production, some areas have less CNTs or no CNTs at all.

In conclusion, the addition of CNTs in the matrix improves matrix dominated fatigue properties of carbon fiber /epoxy composites.

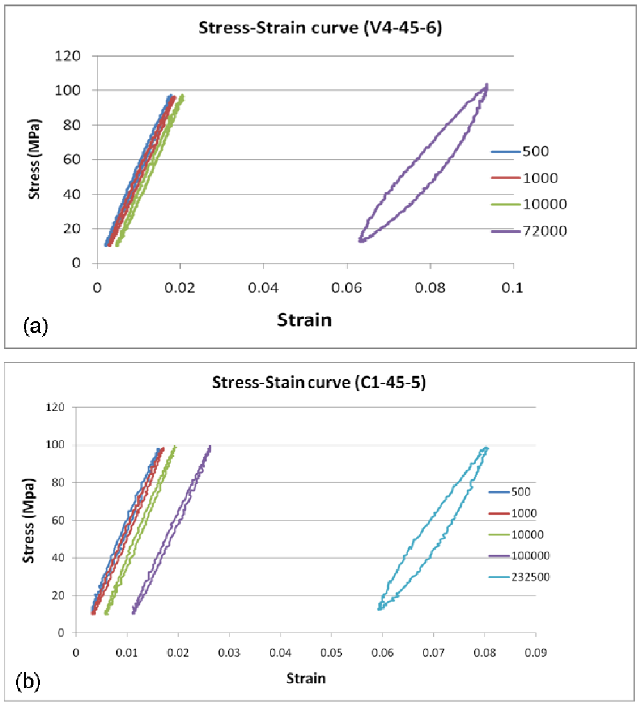

Fig. 4 Stress-strain data from the fatigue test in the bias direction for (a) FRC and (b) nFRC.

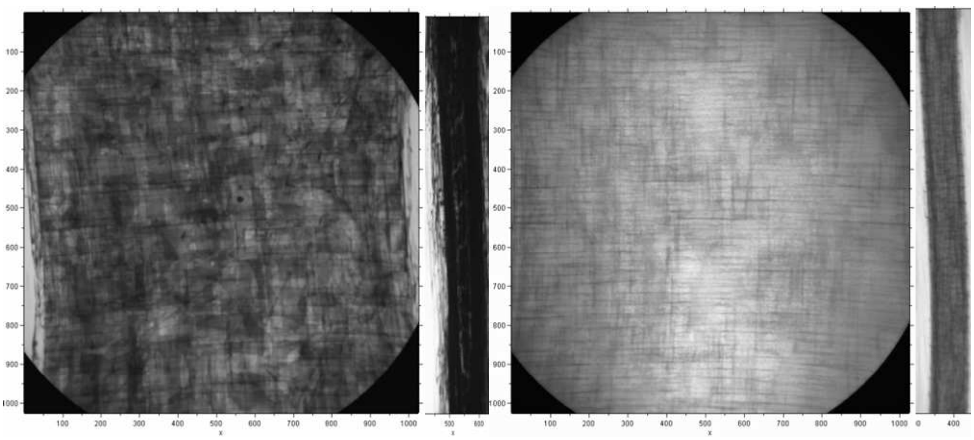

Fig. 5 X-ray images of the failed virgin sample (~1mln cycles) and the unbroken CNT modified sample (~5 mln cycles) after fatigue tests at 500 MPa in the fiber direction.

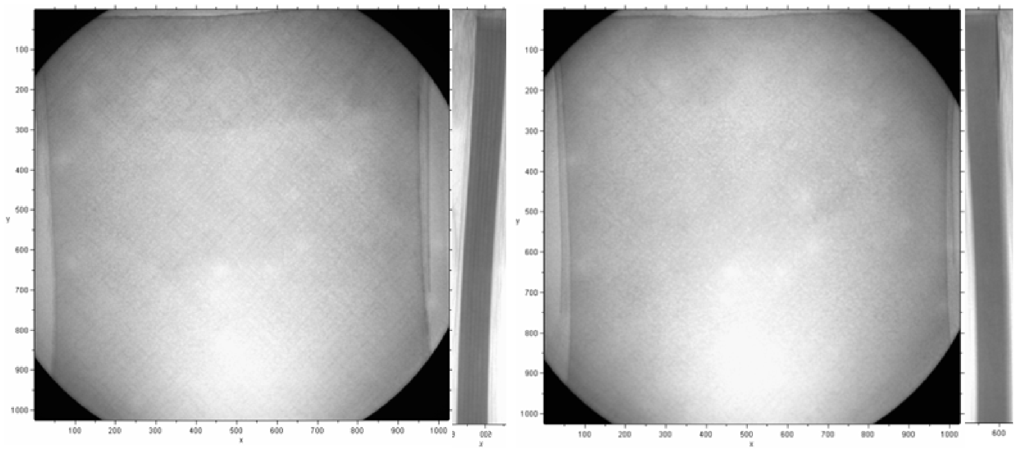

Fig. 6 X-Ray images of FRC (left) and nFRC (right) samples after fatigue test at 100 MPa

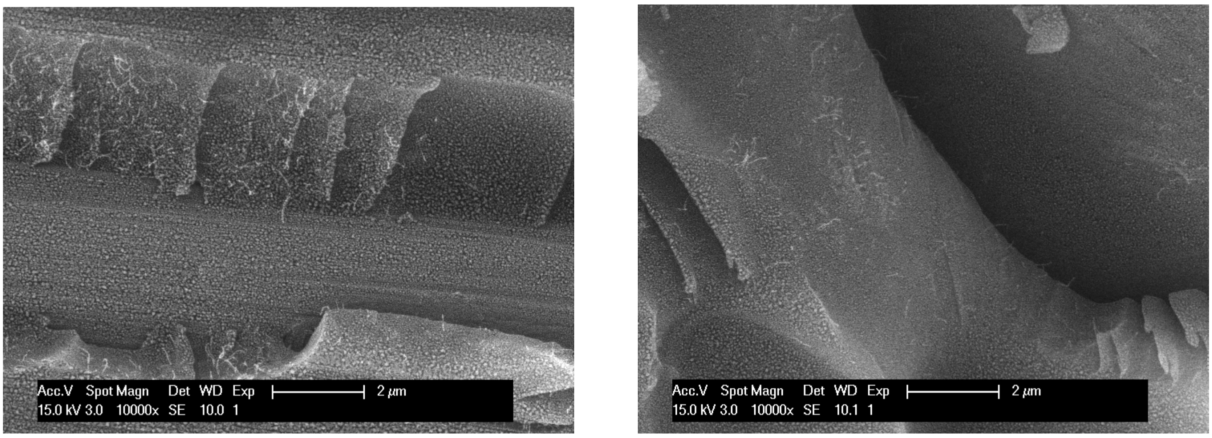

Fig. 7 SEM image of the fatigue fracture surfaces of nFRC showing CNTs in the matrix.

Acknowledgments

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