PECULIARITIES OF DAMAGE BEHAVIOUR OF NCF CARBON/EPOXY LAMINATES UNDER TENSION

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Abstract

Composites reinforced by non-crimp fabrics (NCF) reach stiffness level close to the ideal cross-ply laminates with unidirectional plies, but damage behaviour of NCF-composites exhibit significant differences from the behaviour of the laminates with unidirectional plies (non-stitched laminates). The paper presents results of experimental studies of the initiation and development of damage in NCF-composites. Some of the observed phenomena can be explained and predicted using FE modelling of the composite deformation. Others are difficult to explain; they present a challenge for understanding the behaviour of NCF-composites. The materials are carbon/epoxy composites, reinforced by biaxial NCF 0°/90° and ±45°. Two different sets of fabrics (different producers) were used for the reinforcement, and the fibre volume fraction of the plates had two different levels: about 45% and about 55%. The samples were loaded in different directions in tension. Damage initiation and development was studied using acoustic emission and X-ray investigation.

1. Introduction

The non-crimp fabrics (NCF), also known as multi-axial multi-ply fabrics (MMFs) overcome the problems related to the use of unidirectional prepregs and have attracted much attention of the composite industry. These fabrics consist of unidirectional plies arranged in a number of possible orientations relative to the fabric warp direction; the individual plies are kept together by stitching yarns. This structure leads to an advantageous combination of high material properties and low cost processing, and overcomes the disadvantages of the crimp factor of woven fabrics, providing full use of fibre modulus and strength in ready parts. Compared to the time consuming and expensive UD tape layout, NCF preforms are produced in one step, so the lay up time is drastically reduced. These textile reinforcements have good dimensional stability that allows them to be handled easily in composite production. Their good drapeability makes them suitable for making composites with complicated shapes (for example, double curvature parts). Composites based on multi-axial multi-ply fabrics can be made by traditional lamination, pultrusion and resin transfer moulding (RTM).

Department MTM, K.U.Leuven, has performed an vast program of studies of NCF composites, published in the series of papers [1,2,3,4,5,6,7] and separately [8]. In these studies the same set of NCF was used. The paper focuses of the results of studies of damage behaviour of NCF carbon/epoxy composites, adding to the previous data new results on a new set of fabrics, and accenting the pecularities (some of them still unexplained) of the material behaviour.

2. Materials

In the present paper two biaxial NCF materials are used to illustrate the features of the damage behaviour of NCF carbon-epoxy composites. These two materials use NCF reinforcement from different suppliers and different epoxy resins. The similarities and differences in their behaviour highlight the typical features of damage initiation and development. The parameters of the reinforcements and the composites are shown in Table 1. Fig. 1 shows the fabrics and the test directions.

Note in Table 1 the data on the openings in the fibrous plies created by stitching. The resin rich zones, created by these openings, play an important role in all the aspects of behaviour of the NCF composites [1,4,7,8].

Table 1 NCF reinforcement and carbon/epoxy composite samples

Material ID	B0/90	B45
Fibre orientation	0°/90°	+45°/-45°
Carbon tows	24K	24K
Areal density of NCF, g/m2	307	540
Stitching spacing, mm	5.0x2.6	5.0x3.5
Stitching pattern	Tricot-chain	Chain
Width of the openings, mm, face/back	0.18/0.40	0.26/0.43
Length of the openings, mm, face/back	4.2/channel	9.6/11.9
Number of the plies	8	4
Plate thickness, mm	3.5	2.1
Vf, %	45	56

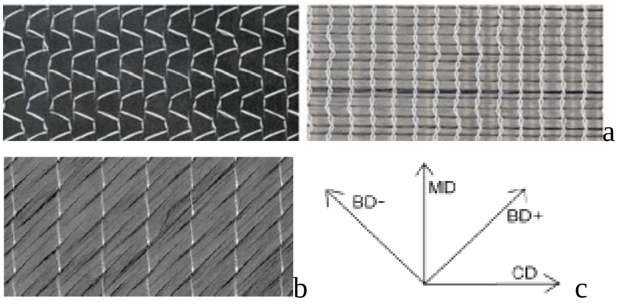

Fig. 1 Fabrics B0/90 (a, face and back) and B45 (b, face), test directions (c).

3. Tensile tests

Static tensile tests were done in the directions shown in Fig. 1. The test speed was 1mm/min. Strain was measured with an extensometer. A minimum of five samples was tested in each direction. Acoustic emission sensors were attached to the samples, to determine the characteristic strain levels of the damage initiation and development, following the methodology described in [9].

4. Damage initiation threshold

Damage initiation, as registered by AE and confirmed by X-ray images, happens on two distinctly different strain levels for loading along the fibres and off-axis tension (Fig. 2, Fig. 3): 0.3%...0.4% and 1.5…2%. These damage initiation threshold of 0.3…0.4% for NCF-composites is significantly lower then the threshold of about 0.6% for ideal cross-ply laminates. The difference is explained by the stress-strain concentration due to the presence of the resin-rich zones at the stitching sites in NCF-composites [4].

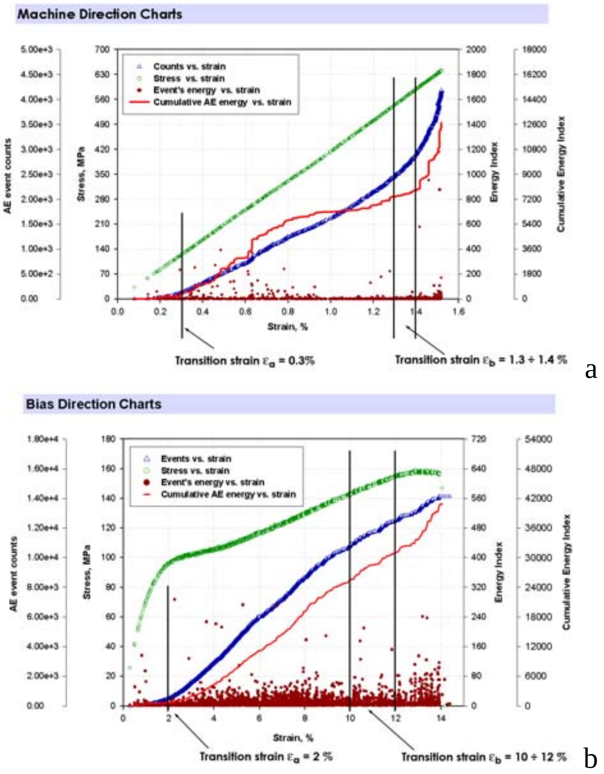

Fig. 2 Stress-strain diagram and AE for B0/90.Tet direction: (a) MD (fibre); (b) BD (off-axis)

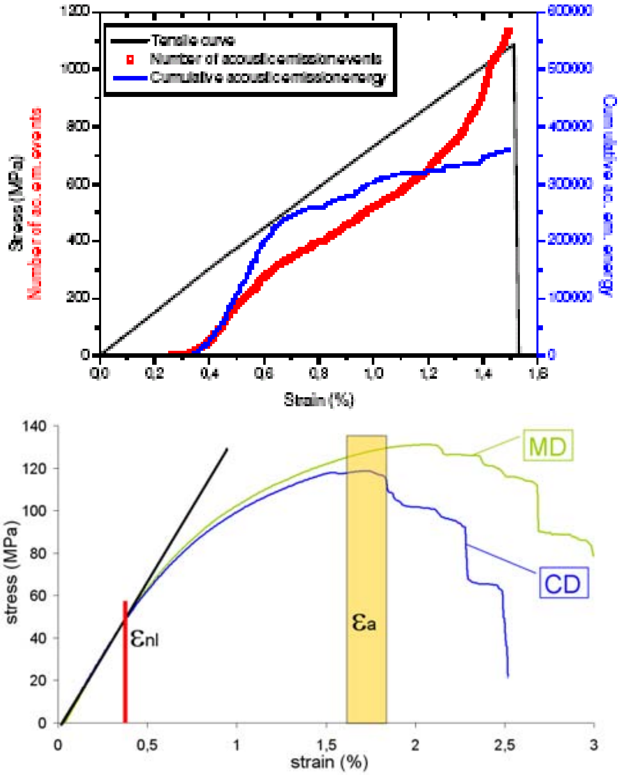

Fig. 3 Stress-strain diagram and AE for B45. Test direction: (a) BD (fibre); (b) MD (off-axis)

The behaviour of the composites B0/90 and B45 loaded in fibre direction is quite consistent. When loaded off-axis, an important difference appears (Fig. 2b, Fig. 3b). Both composites have the same damage initiation level (ca 2%), but their behaviour before and after it differs. *Before* the damage initiation material B0/90 is almost linear; the non-linearity limit coincides with the damage initiation threshold; material B45 is non-linear in the same region, with the non-linearity limit ca 0.4%. *After* the damage initiation material B0/90 deforms further up to 14% strain (with much reduced stiffness); material B45 completely fails at 2.5…3% applied strain. This difference may be caused by non-linearity of the matrix.

5. Finite element modelling

The elastic region of the tensile diagram and damage initiation threshold are well calculated with meso-FE modelling (Table 2). Fig. 4 illustrates FE simulation of tensile loading of composite B45. Calculation predict correctly elastic constants of the material, based on homodenisation of the sress fields (Fig. 4a), and damage initiation threshold using Puck criterion (Fig. 4b). Larger error in the damage initiation strain for off-axis loading may be caused by unexplained (and not implemented in FE) non-linearity of the matrix.

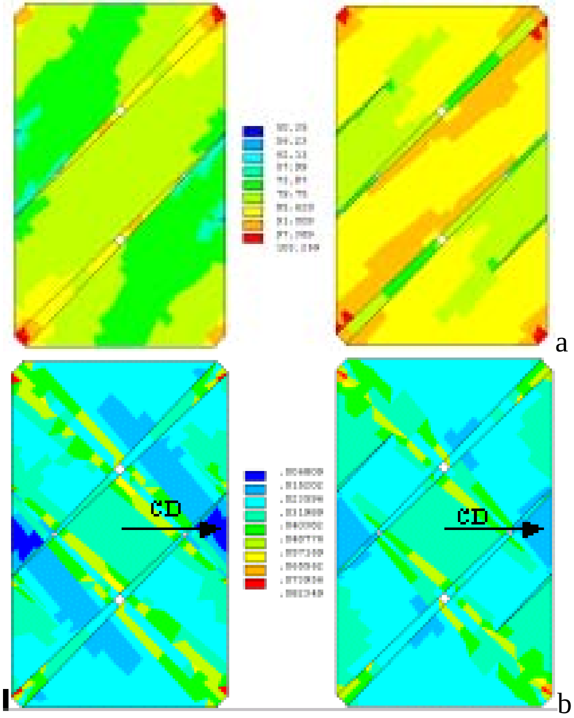

Fig. 4 FE modelling of B45 composite, loading in CD direction: (a) stresses σ_x (x = load direction); (b) values of Puck damage criterion

Table 2 Calculated and measured parameters of composite B45

Parameter	*Load direction*	*Calculated*	*Measured*
Young modulus, GPa	BD+	71.8	68 ± 6
	BD-	71.8	72 ± 2
	MD	15.1	15± 1
	CD	15.1	15± 2
Damage initiation strain, %	BD+	0.37	0.40 ± 0.05
	BD-	0.41	0.36 ± 0.03
	MD	1.84 ± 0.04	1.2
	CD	1.63± 0.14	1.2

6. Damage development: matrix cracking

The damage development sequence in NCF-composites is similar to that observed for non-stitched laminates (Fig. 5). Both in the tests in fibre and of-axis direction, damage starts at very low strain. At the strain of about half of ultimate strain, the damage is quite pronounced. The micro-damage reduces the stiffness of specimens tested in bias direction but it is not the case for specimens tested in fibre direction (Fig. 3, Fig. 4).

The C-scan and X-ray images show that damage in NCF laminates occurs periodically and follows the stitching pattern. Matrix crack density increases with increase of load, finally reaching a saturation level. This behaviour is the same for B0/90 and B45 materials.

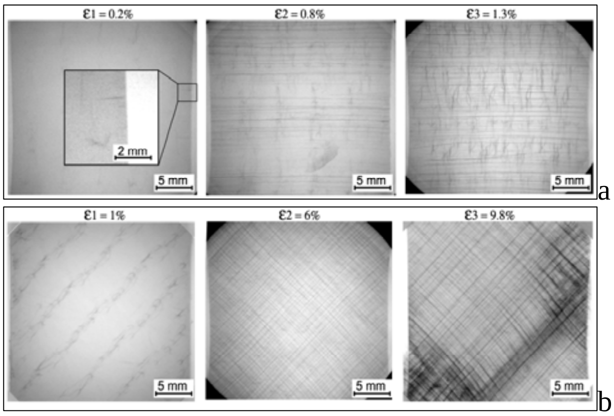

Fig. 5 X-ray images of damage in composite B0/90 for load directions: (a) MD and (b) BD

7. Delamination and fibre failure

The studied NCF-composites exhibit two types of the delamination and fibre failure behaviour when loaded in fibre direction.

The first type of behaviour is similar to the behaviour of non-stitched laminates: delamination at places of high matrix crack density and fibre failure occurs at the late stage of the tensile test. This is observed in the fabric B0/90 (Fig. 5b)

The second type of behaviour is quite peculiar. It was also observed before by Mattson et al [10] in experiments with different NCF-composites. Premature delamination and fibre failure occurs, depending on the layout of the NCF laminate. This effect was not observed for B0/90, which has 45% fibre volume fraction samples. It is present for the material B45 with Vf=55%. However, as the fabrics and resins for these two cases are different, the difference in behaviour cannot be attributed solely to the difference in fibre volume fraction.

Consider testing of the material B45 in directions BD+ and BD-. These test directions correspond to the laminate lay-up as shown in Fig. 6.

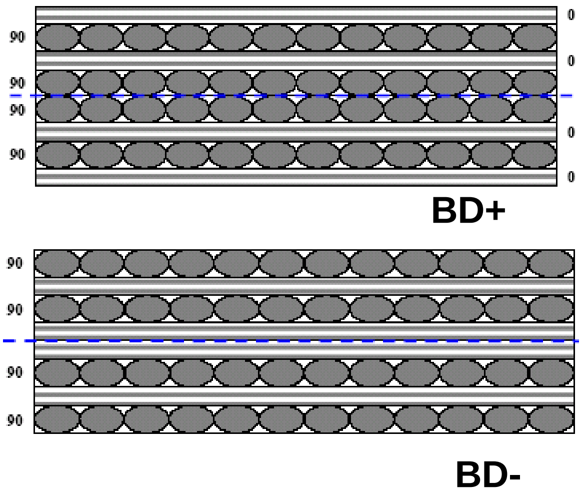

Fig. 6 Composite B45 layup for BD+ and BD- test directions

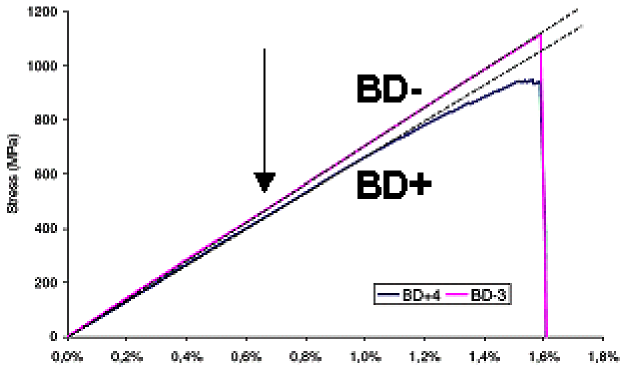

Fig. 7 Tensile diagrams, composite B45, tests in fibre directions. The arrow shows onset of premature fibre failure for BD+ testing

The samples tested in BD+ direction, corresponding to the lay-up with 0° plies on the surface of the sample and 90° plies in the middle, exhibit premature fibre failure in the inner 0° plies at the moment shown by an arrow on the diagrams Fig. 7. This damage is also indicated by AE registration and observed in X-ray and microscopic examination of the samples loaded up to the indicated strain level.

The premature fibre failure results in drop of the sample strength of about 25%. The strain threshold for the damage initiation (matrix cracking) of 0.36…0.40% and the failure strain of 1.5…1.6% are the same for BD+ and BD- samples.

The presence of a double 90° oriented layer perpendicular to the tensile direction might cause earlier failure of 0° fibres, because larger cracks are formed in this layer, leading to higher stress concentrations at the interface with the 0° fibre layers. However, the effect is not fully explained, as well as its absence or presence for a particular material, and should be a subject of future investigations.

8. Sample failure

The final failure of the B45 sample exhibits interesting effect connected with the stitching of the NCFs. As shown in **Fig. 8**, there is a significant difference in the ultimate strain of the samples tested in MD and CD directions, which can be explained by different spacing of the stitching in these two directions (Table 1), making the samples tested in CD weaker (“toilet paper effect”).

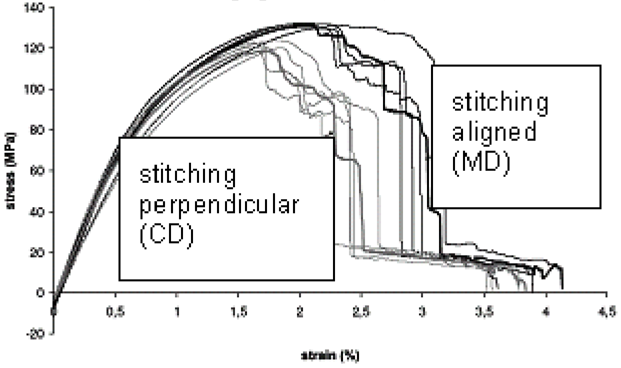

Fig. 8 Tensile diagrams, composite B45, tests in off-axis directions.

This effect is not observed in B0/90 fabrics, as they exhibit very ductile behaviour before the final failure when loaded in off-axis directions (Fig. 2b).

9. Conclusions

We have thoroughly studied damage behaviour of NCF carbon/epoxy composites and have observed a number of characteristic features and peculiarities. Some of these are explained and predicted by FE modelling, but there is still some presenting a challenge, especially the premature fibre failure effect.

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