THE TRANSITION FROM OUT-OF-PLANE TO IN-PLANE KINKING DUE TO OFF-AXIS LOADING

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Abstract

A comprehensive test campaign has been performed on coupon level to gain fundamental understanding of compressive failure in unidirectional NCF composites for aerospace applications. A subset of this study is focusing on the effect of off-axis loading, where a number of laminates have been tested with fibres oriented in off-axis angles in the interval 0-20° in steps of 5°. Our hypothesis is that 0° laminates fail by kinking out-of-plane and as the off-axis angle is increased, there is a shift to in-plane kinking as the in-plane shear component increases. The contribution from this shear component on kinking will have little effect on the compressive strength until in-plane kinking becomes “dominant” over out-of-plane kinking. Preliminary results indicate a transition from out-of-plane to in-plane governed kinking to occur at an off-axis angle between 10° and 15°.

1. Introduction

It is well understood that the kinking process is driven by shear stresses, which degrade the polymer material and subsequently removes the support for the load carrying carbon fibres. There are however details in this process that have not yet been fully explored. Understanding of the orientation of the kink-band and its dependence on off-axis loading is critical for accurate modelling of compression failure.

In this paper, we present an experimental study focusing on the effect of off-axis loading, which is a subset of a comprehensive test campaign pursued to gain fundamental understanding of compressive failure in unidirectional non crimp fabric (NCF) composites for aerospace applications [1]. Here, a number of laminates have been tested with fibres oriented in off-axis angles in the interval 0-20° in steps of 5°. When tested in compression, all these laminates failed by kinking of the fibres, which confirms previous observations by Edgren et al. who found multiaxial NCF composites to fail by kinking under compression loading at off-axis angles up to 20° [2]. The opportunity to study this is given by Fig 1, which illustrates how most of the laminates failed. The laminates have kink-bands with some amount of un-broken fibres. The progressive behaviour is explained by the large fibre waviness present in the laminates.

Additional work is in progress to provide a detailed explanation to the effect of kink-band formation from increased off-axis loading. Firstly, a numerical approach to model the compression tests with finite elements incorporating damage and fibre misalignment angles from measured fibre waviness. Secondly, fractographical results from micro-computed tomography (CT) will provide accurate information of the kink-bands. In this paper we are limited to the experimental strength observations and manual macroscopic measurements of kink-band angles.

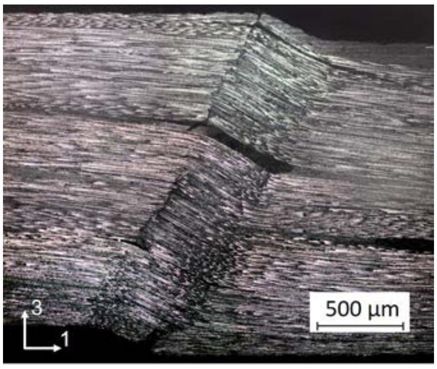

Figure 1. Micrograph of a kink-band oriented through the thickness of a unidirectional NCF composite.

2. Method

2.1. Material and specimens

The unidirectional composite laminates are based on HTS45 carbon fibres and LY556 epoxy resin. The textile consists of 12k bundles that are held together by a polyamide/glass yarn in the weft direction. There are 2.4 bundles/cm and one weft yarn/cm. The thickness of the textile is 0.3 mm and becomes approximately 0.2 mm at a V_f of 53%. The areal mass is 205 g/m^2 for the textile and 192 g/m^2 for the fibres, calculated without sizing. The RTM process was used to fabricate the laminates with data presented in Table 1. Glass/epoxy laminate tabs with a thickness of 1.6 mm were adhesively bonded on each side before water-cutting the specimens. The specimens were produced for testing with ASTM D6641 and ASTM D3410 standards [3,4] with nominal size of 140 × 12 × 2 mm (length × width × thickness) and a gauge section length of 13 mm. The effect of specimen width on compression strength has been studied with the conclusion that 12 mm is a sufficient width [5]. The maximum fibre misalignment angle out-of-plane θ_{max} governing the compressive strength was characterised by Wilhelmssson et al. [1] and was found to be 8.0° for laminate B2. Measurements on a few specimens indicate similar values for laminate D1-D4.

Table 1. Basic properties of manufactured laminates where *n* is the number of valid tests and *t* is the thickness. The fibre volume fraction V_f is calculated based on the areal weight and density of the fibres.

Laminate	*n*	Layup	*t*	V_f
B2	7	$[0]_{10}$	2.03	53
D1	8	$[5]_{10}$	2.03	53
D2	7	$[10]_{10}$	2.03	53
D3	12	$[15]_{10}$	2.03	53
D4	12	$[20]_{10}$	2.03	53

2.2. Compression tests

Compressive testing was performed according to ASTM D6641 [3] and ASTM D3410 [4] to characterise the material strength. The CLC fixture used for ASTM D6641 [3] was made at Swerea SICOMP according to the standard and the ITRII fixture used for ASTM D3410 [4] was manufactured by Wyoming Test Fixtures. Testing was conducted at the Swerea SICOMP laboratory in Mölndal, Sweden, in a 100 kN MTS 20/M load rig. The compressive load was applied at a rate of 1.3 mm / min until a drop in load was observed. Bending in the specimens was monitored with strain measurements on a few specimens from each laminate according to the ASTM standards [3,4]. Both of these standards allow a maximum of 10% bending at failure for a test to be considered valid and it is noted in Table 2 that the three out of five laminates exceeded this requirement. The problem with bending has been thoroughly investigated with the conclusion that it has no significant effect on the compressive strengths in these tests [1].

Table 2. The number of specimens with strain gauges n_ε, IITRI or CLC fixture and average bending at failure within a laminate B_f.

Laminate	n_ε	*IITRI / CLC*	B_f
B2	7	1/6	44
D1	8	3/5	24
D2	7	2/5	8
D3	11	2/10	16
D4	11	2/10	8

3. Results and discussion

Unlike the 0° laminate, where kinking occured out-of-plane (Fig. 2a), the off-axis laminates are found to have a component of kinking in-the-plane (Fig. 2b). Furthermore, as the off-axis angle increases the in-plane kinking component increases and becomes more evident. While CT scans are currently ongoing, an attempt has been made to characterise this progression by simpler means. Two specimens from each laminate were characterised with an optical microscope in terms of the kink offsets according to Fig. 2. The average of the two off-set values for each laminate is reported in Table 3 as a ratio between the in-plane and out-of-plane components. As reported in a previous study [1], all zero degree laminates failed by kinking out-of-plane, i.e. an in-plane component of zero and an out-of-plane component of one in Table 3. A kink-plane angle of 45° thus corresponds to a ratio 0.5 both for the in-plane and out-of-plane component. As can be seen from the data in Table 3, the in-plane component becomes larger as the off-axis angle is increased.

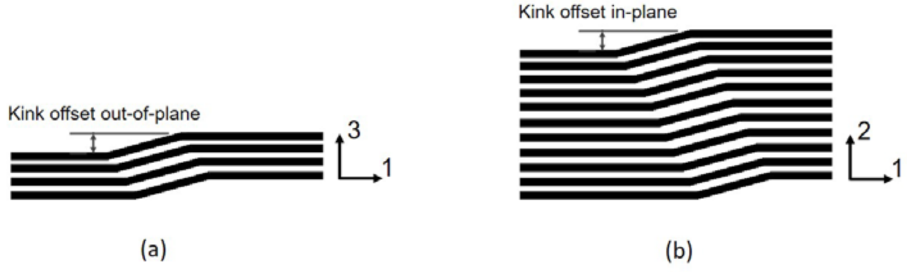

Figure 2. Schematic illustrations of kink-band offset are presented for out-of-plane kinking in (a) and in-plane kinking in (b).

As seen in Table 4 and Fig. 3, there is no significant reduction in compressive strength until the off-axis angle reaches 15°, where a sudden drop in strength is observed. Our hypothesis is that 0° laminates fail by kinking out-of-plane and as the off-axis angle is increased, so is the in-plane shear component, which will promote in-plane kink-band formation. The contribution from this shear component on kinking will have no effect on the compressive strength until in-plane kinking become "dominant" over out-of-plane kinking. Preliminary results, indicate the switch from out-of-plane to in-plane governed kinking to occur between 10° and 15° in this specific case. Interestingly, preliminary measurements confirm this as the in-plane component becomes equal to or larger than the out-of-plane component at 15°. We expect the transition to be dependent on the magnitude of fibre waviness out-of-plane i.e. higher fibre waviness out-of-plane requires higher off-axis angles to reach the transition from out-of-plane to in-plane dominated kinking. The laminates in this study all have maximum out-of-plane fibre misalignment angles of approximately 8.0°, which corresponds to high fibre waviness.

Table 3. The ratio of kinking in-plane and out-of-plane.

Off-axis angle	0°	5°	10°	15°	20°
In-plane component	0	0.20	0.37	0.50	0.77
Out-of-plane component	1	0.80	0.63	0.50	0.23

Table 4. Summary of compression test data with associated errors.

Laminate	X_c (MPa)	CV_{Xc} (%)	E (GPa)	CV_E (%)	E_{cu} (%)
B2	394	13	102	16	0.39
D1	405	9	88	10	0.48
D2	394	12	65	5	0.72
D3	297	7	43	8	0.95
D4	258	3	33	5	1.31

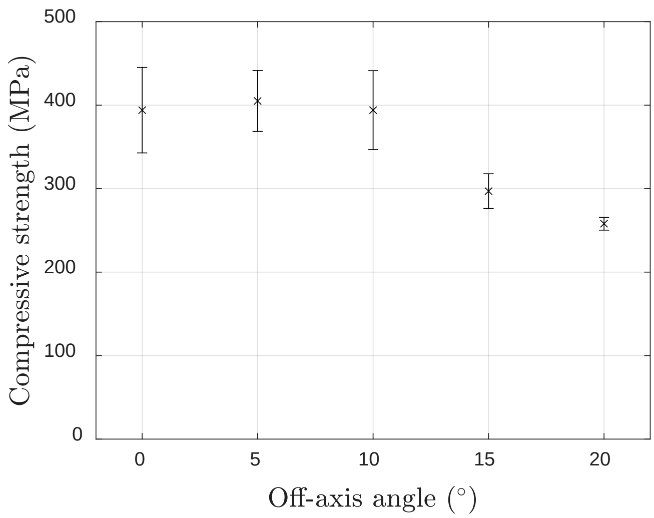

Figure 3. Compressive strength as a function of off-axis angle with associated standard deviations.

4. Conclusions

An experimental study has been conducted on unidirectional NCF composite specimens with varying off-axis angles. Experimental strength results show that a sudden drop occurs in strength between an off-axis angle of 10° and 15°. The hypothesis is that in-plane shear stress due to off-axis loading has limited contribution to kinking until the kink-component in-plane becomes dominant. Preliminary measurements confirm this hypothesis.

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