ICF100950OR

COMPRESSIVE FRACTURE OF ORTHOTROPIC LAMINATES CONTAINING OPEN HOLES DUE TO FIBRE MICRO-INSTABILITY

Constantinos Soutis

Department of Aeronautics, Imperial College of Science, Technology and Medicine
Prince Consort Road, London SW7 2BY, UK

ABSTRACT

The compressive strength and failure mechanisms are investigated for a wide range of filamentary composites. Static uniaxial compressive tests are performed on both notched and unnotched specimens made from four carbon fibres and three epoxy resins combined to give six different composite systems. In all cases the dominant failure mechanism is by fibre microbuckling (fibre kinking). An infinite band-kinking model is used to estimate the unnotched strength and a linear softening cohesive zone model is applied to estimate the open hole compression (OHC) strength.

KEYWORDS

Composite materials, laminate, fibre microbuckling, kinking, cohesive zone model, compressive strength.

INTRODUCTION

The compressive strength of long, aligned carbon fibre-reinforced plastics (CFRP) is significantly lower than the tensile strength of the material due to kink-band formation introduced by fibre instability (microbuckling). In contrast, the compressive strength of metallic materials equals or exceeds their tensile strength (by an order of magnitude for ceramics). From the literature on compressive fracture it is easy to get the impression that fibre microbuckling and kinking are two different competing mechanisms. In fact, the kink band is the outcome of fibre microbuckling failure, as observed experimentally in [1-3]. Fibre microbuckling occurs first, followed by propagation of this local damage to form a kink band. Many analytical models attribute the low compression strength and the mechanism of kink-band formation to initial fibre misalignment (waviness) but fibre and fibre-matrix interface properties may also play an important role. In a multidirectional laminate the supporting ply orientation on the stability of the 0° layer (ply-ply interaction) and the location of the 0° ply through the laminate thickness can also have a significant effect on the initiation and final failure. For instance, the failure strain of a laminate with 0° outer layers can be more than 10% lower than a similar lay-up with ±45° outer plies, due to out-of-plane fibre microbuckling [4]. The outer off-axis plies provide better lateral support to the 0° layers, permitting them to fail by in-plane microbuckling, which is a higher strain failure event.

In the present paper, compressive tests are reported for several carbon fibre-epoxy systems and lay-ups with and without holes; the failure mode is fibre microbuckling in all cases.

FRACTURE ANALYSIS

Unnotched Compressive Strength

It is now well established that the unnotched strength, σ_c, of unidirectional carbon fibre-epoxy laminates is governed by fibre microbuckling which is associated with non-linear shear of the polymer matrix initiating from regions of pre-existing fibre waviness (of magnitude only few degrees). For a rigid-perfectly plastic body Budiansky [5] showed that

$$\sigma = \frac{\tau_y \left[1 + \left(\frac{\sigma_{T_y}}{\tau_y} \right)^2 \tan^2 \beta \right]^{\frac{1}{2}}}{\phi_0 + \phi} \qquad (1)$$

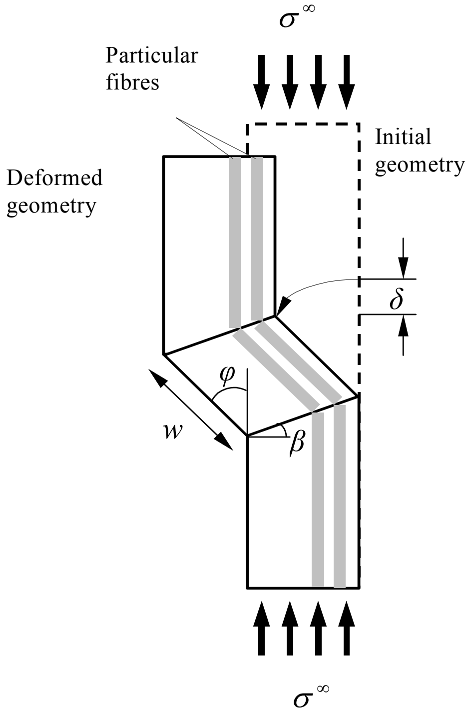

Figure 1. Fibre kink band geometry

where τ_y and σ_{Ty} are the in-plane shear and transverse yield stresses of the composite, respectively. ϕ_0 is the assumed fibre misalignment angle in the kink band, ϕ is the additional fibre rotation in the kink band under a remote stress σ^∞, and β is the band orientation angle, Fig.1. The critical stress $\sigma=\sigma_c$ is achieved at $\phi=0$ in equation (1).

By using the above kinking theory, the unnotched strength of the unidirectional laminate can be obtained in terms of the shear properties of the composite and the initial fibre misalignment. Once the failure stress of the 0°-ply is known, the compressive strength of any multidirectional 0°-dominated lay-up can be estimated by the stiffness ratio method,

$$\sigma_{un} = \frac{\sigma_c}{NE_1} \sum_{k=1}^{N} n^{(k)} E_{x\theta}^{(k)} \qquad (2)$$

where σ_{un} is the unnotched laminate strength, σ_c is the strength of the 0° lamina, N is the total number of the laminae in the laminate, E_1 is the 0° ply stiffness in the fibre direction, n is the number of plies of a given orientation θ, and $E_{x\theta}$ is the modulus of a ply of orientation θ in the loading direction (x).

Open Hole Compressive Strength

Soutis and co-workers [2, 6, 7] have developed a crack bridging model for the initiation and growth of compressive damage from the edge of a blunt notch such as an open hole. The microbuckled region (and associated plastic deformation in the off-axis plies and delamination between plies is treated as a compressive *Mode I* crack with a cohesive zone at its tip. A linearly softening spring law within the cohesive zone models damage: the crack bridging normal traction T is assumed to decrease linearly with increasing crack closing displacement (CCD) $2v$ from a maximum value (equal to the unnotched strength σ_{un} of the composite) to zero at a critical crack face displacement of $2v_c$. The intrinsic toughness at the tip of the cohesive zone is taken equal to zero, which is similar to the Dugdale analysis of plastic deformation in metals from the root of a notch [8]. Rice [9] has shown that the work done G_C to advance the crack equals the area under the crack traction versus crack displacement curve, giving $G_C=\sigma_{un}v_c$. The cohesive zone model may be used to predict the notched strength σ_n of any multidirectional laminate once the material parameters σ_{un} and G_C have been measured from independent compression tests [2, 6].

Alternatively, the unnotched compressive strength can be estimated from equations (1) and (2) and the critical crack closing displacement can be related to the kink band width w [5, 7], i.e.,

$$w = 2v_c = \frac{\pi d_f}{4}\left(\frac{V_f E_f}{2\tau_y}\right)^{\frac{1}{3}} \tag{3}$$

where d_f is the fibre diameter, E_f is the fibre elastic modulus, V_f is the fibre volume fraction and τ_y is the in-plane shear yield strength of the composite. Equation (3) implies that the broken fibres in the cohesive zone model rotate completely and do not lock up ($2v_c=\delta_c$, see Fig.1).

MATERIALS AND TESTING PROGRAMME

Four carbon fibres and three epoxy resins were combined to give six composites, as shown in Table 1. The materials were supplied in prepreg form by Hexcel Composites, and autoclave cured to produce a variety of laminates.

TABLE 1
COMPOSITE SYSTEMS STUDIED

Composite	Fibre	Matrix Resin
1	T800	922
2	T800	924
3	T800	927
4	T300	927
5	IMS	927
6	HTA	927

T800 (Torayca) and IMS (Tenax) are equivalent intermediate modulus fibres (about 290GPa) with tensile strain to failure of about 1.9%. T300 (Torayca) and HTA (Tenax) are equivalent low modulus fibres (about 235GPa) with tensile strain to failure of about 1.5%. The three Hexcel resins increase in tensile strength, failure strain and toughness from 922 through 924 to 927 [10, 11].

Unidirectional specimens were tested in compression according the Imperial College method [10], which uses a 10mm gauge length Celanese-style specimen, and according to the modified Celanese method [1, 3]. Collected results are given later. Notched specimens were tested in compression according to the ACOTEG standard ACO/TP/II [10, 11]. Specimens were 36mm wide and contained a 6mm diameter central hole. The laminates were nominally 3.5mm thick with the lay-up $[0/45/-45/0/90/0/45/-45/0/90/0/45/-45/0°]_s$. Specimens were supported in an anti-buckling guide to prevent overall buckling[2]. The extent of the internal damage in the specimens was assessed by ultrasonic scanning [10].

RESULTS AND DISCUSSION

Unidirectional Compression

The results from the unidirectional compression tests are presented in Table 2. The measured compressive strengths for the six composite systems examined are in very good agreement with the theoretical values, predicted by the Budiansky plastic fibre microbuckling model [5]. The model requires the knowledge of the initial fibre misalignment (ϕ_0), the shear yield stress (τ_y), the transverse tensile yield stress (σ_{Ty}) and the kink band inclination angle (β). Although the six composite systems demonstrate different ultimate shear strengths, their shear yield stresses, which mostly influence the unidirectional compressive response, are very similar at 65-70 MPa. Taking ϕ_0=3° (0.052 rad), τ_y=70MPa and β=15° (0.262 rad) gives a satisfactory overall prediction, as seen in Table 2. These values are close to values found from experimental observations for all materials. Of course, the effect of fibre strength and stiffness properties, fibre diameter and fibre/matrix interface, are not accounted for by the model and they may influence the composite strength. A weak interface may trigger microbuckling prematurely, while a bigger fibre diameter will provide higher buckling resistance [4].

TABLE 2
STIFFNESS AND STRENGTH PROPERTIES OF A UNIDIRECTIONAL LAMINATE

Composite System	E_1 GPa	E_2 GPa	G_{12} GPa	ν_{12}	σ_c^{th} MPa	σ_c^{exp} MPa	difference %
T800/922	143.6 (158)#	9.9	3.98	0.29	1440	1410	-2.08
T800/924	141 (158)	8.6 (9.0)	4.12 (6.0)	0.33	1440	1350 (1448)	-6.25
T800/927	154	8.32	3.75	0.37	1440	1450	-
T300/927	116 (131)#	7.5 (8)#	3.56+	0.31	1440	1450	-
IMS/927	135 (175)#	8.2	3.56+	0.33	1440	1320	-8.3
HTA/927	118 (145)#	6.8 (8)#	3.24+	0.35	1440	1530	5.9
$\overline{\sum}$	137.4	8.3	4.02	0.33	1440	1435	-

Notes: ( ) Experimental data measured by Soutis et al [3,4]
\+ Estimated values from the resin shear modulus and fibre volume fraction
\# Expected values
σ_c^{th} Predicted strength
σ_c^{exp} Measured strength

Multi-directional Compression

The notched compressive strength (σ_n) of a multi-directional laminate is assessed with reference to the unnotched strength (σ_{un}). Details of the latter are given in Table 3. In the present study problems were experienced in the experiments due to the laminates failing adjacent to the grips, outside the region supported by the anti-buckling guides. The values given in the table will, therefore, be underestimates of the true value.

TABLE 3
PREDICTED STIFFNESS AND STRENGTH PROPERTIES OF A
$[0/\pm45/0/90/0/\pm45/0/90/0/\pm45/0]_S$ LAMINATE

Composite System	E_{xx} GPa	E_{yy} GPa	G_{xy} GPa	ν_{xy}	σ_{un}^{th} MPa	σ_{un}^{exp} MPa
T800/922	75.5	40.2	18.2	0.390	728	640.5 (±37)
T800/924	74.08	39.06	17.84	0.398	743.8	636.9 (±23)
T800/927	80.1	41.7	19.0	0.403	743.8	660.8 (±55)
T300/927	61.17	32.46	14.85	0.386	742.1	n/a
IMS/927	70.61	37.15	16.9	0.396	739.2	n/a
HTA/927	61.74	32.35	14.8	0.395	744.6	n/a

The theoretical compressive strength has been obtained by using Eq.(1) taking σ_{Ty}=100 MPa, τ_y=70 MPa, ϕ_0=3° and β=15° and Eq.(2). The measured unnotched strength is at least 15% lower than the predicted value due to premature (grip) failure. The stiffness ratio method predicts 728 MPa (assuming

σ_0=1440 MPa for all systems), while the result obtained from the maximum stress or strain criterion is 757 MPa (assuming σ_0=1440 MPa, or an average failure strain of 1%). The elastic stiffness properties in Table 3 are calculated values using ply properties (Table 2) and classical laminate theory.

TABLE 4
NOTCHED COMPRESSIVE STRENGTH OF A $[0/\pm45/0/90/0/\pm45/0/90/0/\pm45/0]_s$ LAMINATE (hole diameter=6mm, d/w=0.167)

Composite System	τ_y **MPa**	ϕ_0 **o**	β **o**	σ_{un}^{th} **MPa**	σ_n^{th} **MPa**	l_c **mm**	σ_n^{exp} **MPa**
T800/922	70	3	15	728	368.1	1.95	370.4 (±8)
T800/924	70	3	15	743.8	371.3	1.86	390.0 (±4)
T800/927	70	3	15	743.8	371.2	1.86	377.0 (±6)

The theoretical notched strength (σ_n) and critical microbuckling length (l_c) at the hole edges are simulated by the Soutis *et al* [2, 6] cohesive zone fracture model. For the T800 composite system, using equation (3) and material data (V_f=0.65, E_f=294 GPa, τ_y=70 MPa) a width of about 10 fibre diameters (≈60 μm) is obtained, which is representative of observed kink band widths of 60-80 μm [2, 6]. Using the theoretical unnotched strength (Table 3) and a value of v_c=40 μm appears to predict the notched strength of all three T800 systems very accurately, as seen in Table 4; similar good correlation is expected for the three other systems (T300-, IMS- and HTA-927). The predicted critical microbuckling length is also included in Table 4. When this value is reached the laminate is expected to fail catastrophically. Microbuckling lengths of 2-3 mm, depending on hole size and lay-up, have been observed experimentally [2, 6]. Microbuckling of the 0° plies nucleates at the sides of the hole at between 75-80% of the failure load and is accompanied by matrix cracking of the off-axis plies and delamination between neighbouring plies. This damage reduces the stress concentration at the edge of the hole and delays final failure to higher applied stresses. The OHC strengths of all these materials lie below the limit of notch insensitivity (where the net section failure stress equals the unnotched strength) but above the perfectly brittle limit (where the local stress at the root of the notch equals the unnotched strength). Applying the maximum stress failure criterion could underestimate the notched compressive strength by more than 30%, especially for small *d/w* ratios [6]. The material length l_c serves as a useful measure of laminate damage tolerance.

CONCLUDING REMARKS

The fibre kinking model by Budiansky [5] suggests that fibre microbuckling is a plastic rather than an elastic failure mode and that the strength of the unidirectional material is governed by the shear yield stress of the composite and the misalignment angle of the fibre. Applying the model to six different carbon fibre-epoxy systems tested in [10], a very good agreement is found. Although the six systems have different ultimate shear strengths, their shear yield stresses are very similar at 65-70 MPa. Once the failure stress of the 0°-ply is known, the compressive strength of any multidirectional laminate containing 0° layers can be determined on a ply-by-ply analysis using the laminate plate theory and the maximum stress failure criterion. For 0°-dominated lay-ups the strength can be accurately estimated by the stiffness ratio, equation (2). The 18-30% discrepancy observed between predictions and the measured multidirectional unnotched compressive strengths for the six systems examined in [10] is due to Euler bending that occurred during testing and thickness variation across the specimen width. Unnotched strength data are more difficult to generate than tensile data because compression testing is sensitive to factors such as Euler buckling, specimen geometric imperfections, specimen misalignment in the test fixture and fibre misalignment in the specimen.

The linear softening cohesive zone model of Soutis *et al* [2, 6] successfully predicts the effects of an open hole and lay-up upon the compressive strength and microbuckle zone size at failure. In the analysis, the inelastic deformation associated with fibre microbuckling and matrix plasticity developed at the hole edges is mathematically replaced with a line-crack loaded across its faces by a bridging normal traction that decreases linearly with the overlap displacement of the microbuckle. The model takes as its input the laminate unnotched strength and the critical crack closing displacement, which is related to the in-plane compressive fracture toughness of the laminate. A value of 40 μm appears to give an excellent correlation between predicted and measured OHC data for all systems and lay-ups examined in [10]. The cohesive zone approach offers a technique for the prediction of OHC strength, which is simple and easy to apply and has the prospect of being used as a preliminary design tool for laminated polymer composite structures.

ACKNOWLEDGEMENTS

The author would like to thank his research students for assisting with the collection of experimental data and the Engineering and Physical Sciences Research Council and the British Ministry of Defence for financial support.

REFERENCES

1. Soutis, C. (1991) *Comp. Sci. & Techn.*, **42**(4), 373-392.
2. Soutis, C., Fleck, N.A. and Smith, P.A. (1991) *J Comp. Mat.*, **25**, 1476-1498.
3. Soutis, C. (1997). In: *Composite Materials: Testing & Design*, Thirteenth volume, ASTM STP 1242, S.J. Hooper, Ed., American Society for Testing & Materials, 168-176.
4. Berbinau, P., Soutis, C.,Goutas, P. and Curtis, P.T. (1999) *Composites A*, **30**(10), 1197-1207.
5. Budiansky, B. (1983) *Computers & Structures*, **16**(1), 3-12.
6. Soutis, C., Curtis, P.T. and Fleck, N.A. (1993) *Proc. R. Soc. London A*, **440**, 241-256.
7. Soutis, C. and Curtis, P.T. (2000) *Composites: Part A*, **31**, 733-740.
8. Dugdale D.S. (1960) J. Mech. Phys. Solids, 8, 100-104.
9. Rice, J.R. (1968). In: *Mathematical Analysis in the Mechanics of Fracture*, **2**, Academic Press, N.Y.
10. Smith, F.C. (2000) *PhD Thesis*, Imperial College, London, UK.
11. Soutis, C., Smith, F.C. and Matthews, F.L. (2000) *Composites: Part A*, **31**, 531-536.