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Folding of woven composite structures

J.C.H. Yee, S. Pellegrino*

Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK

Abstract

This paper investigates one-ply and two-ply laminates made from woven T300 carbon fibre and Hexcel 913 and 914 epoxy resins. These laminates are of interest for deployable structures applications. The maximum surface bending strain, measured by means of a large-displacement buckling test, is found to be 2.8% for one-ply and 1.9–2.2% for two-ply specimens in the direction of the fibres. In tension, the maximum strains in the fibre direction are 0.9–1.0% and in compression 0.4–1.0%.

Keywords: A. Fabrics/textiles; A. Laminates; D. Mechanical testing; Bending failure

1. Introduction and background

Self-deployable carbon fibre reinforced plastic (CFRP) booms with integral self-locking hinges that are made by cutting three parallel slots in a thin-walled tube with circular cross-section are currently being developed. The slots divide the tube into three strips with curved cross-section, which can be flattened transversally and then bent longitudinally to form an elastic hinge such as that shown in Fig. 1. The inspiration for this foldable structure design comes from *tape-spring* hinges, made from short lengths of steel tape measure, which have been used successfully many times as deployment mechanisms for spacecraft and other applications [1,2]. It is envisaged that integral CFRP tape-spring hinges will provide a lightweight, reliable, low-cost deployment mechanism for deployable booms, solar arrays, etc. to be used on the next generation of small satellites.

The elastic folding of tape springs made of isotropic material is well understood [3–5]; the key features being that they form a *folded region* that is approximately straight transversally and uniformly curved longitudinally, with a radius of curvature equal to the radius of the cross-section of the undeformed tape spring. Also, and remarkably, the curvature of the folded region is the same for 'equal sense' and 'opposite sense' folding, i.e. for both longitudinal curvatures in the same sense and opposite sense, respectively, to the original transverse curvature. The strain and hence stress distribution in the fold region can be straightforwardly determined from the elastic curvature changes, and it can be shown that the radius of transverse curvature to thickness ratio, R/t, of a tape spring has to be greater than $E/[\sigma_y(1-\nu)]$ to avoid yielding of the material (here E is the Young's Modulus, σ_y the yield stress, and ν the Poisson's ratio of the material).

Extending these results to anisotropic materials is straightforward [6,7], but it is then found that tape springs made from woven prepregs are able to survive larger surface bending strains than the ultimate failure strains that are measured from standard coupon tests in tension and compression.

Effects of this type have been observed before. Wisnom [8] carried out bending tests on 26-ply unidirectional XAS/913, 3.35 mm thick specimens, and the observed strains were up to 2.5% on the compression surfaces. In pure compression, the maximum strain observed for this material was typically around 1%. More recently, the existence of specimen size effects has been identified, see the extensive review in Ref. [9], whereby the maximum compressive strain at failure decreases when the dimensions of the specimen are increased. However, all previous work has been on relatively thick specimens; there is no previous work on the bending of very thin composites, which are essential for the design of structures that are able to fold elastically to a small radius. Furthermore, there is only limited published data on laminates made from woven

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* Corresponding author.
E-mail address: pellegrino@eng.cam.ac.uk (S. Pellegrino).

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Fig. 1. Deployable CFRP boom hinge (unfolded, folded 110°, folded 180°).

fabrics [10], which are of specific interest for the present paper.

One-ply and two-ply laminates made from carbon fibre fabric (plain weave) with bi-directional fibres are investigated. The aim of this paper is to characterise and compare the maximum strains before failure in tension, compression and bending by means of simple coupon tests. Measuring the actual compressive strength of a laminate is challenging. The procedure adopted here is based on a sandwich column layout [11] and the average measured strength is found to correlate well with predictions based on measurements of fibre waviness from micrographs of the laminates. The maximum strains in the fibre direction are 0.9–1.0% in tension, 0.4–1.0% in compression, and 1.9–2.8% in bending.

The paper is presented in five sections. Following Section 1, Section 2 describes the materials used in this study and then briefly illustrates the experimental methods used for the investigation. Section 3 presents the experimental results obtained, and is followed by the estimation of the compressive strength and maximum strain in compression of one-ply specimens. A discussion concludes the paper.

2. Experimental method

All specimens were made from prepregs supplied by Hexcel, based on the low curing temperature 913 epoxy resin (prepreg 913C-814-40%) and the 914 toughened epoxy resin (prepreg 914C-814-40%). These prepregs use the same plain weave T300 carbon fabric (3K fibres per tow) and have a 40% resin content by weight; the dry fabric and the prepreg weigh 193 and 322 gsm, respectively. During curing, the 913 prepregs were sandwiched between two steel plates, which resulted in a smooth finish on both sides. The 914 prepregs were cured directly in contact with the bleeder on one side, resulting in a rough surface finish. The thicknesses of the smooth specimens are 0.22 mm (one ply) and 0.43 mm (two plies), and are very uniform. The thickness of the rough specimens is much more variable, see Fig. 8, and average values of 0.23 mm (one ply) and 0.46 mm (two plies) were obtained from several measurements with a micrometer. Each type of laminate was made as a single plate, from which individual specimens were cut with a circular diamond saw.

All tests were conducted using an Instron 4483 materials testing machine with a load cell of 150 kN. Longitudinal strain measurements were made with an LE-05 Electronic Instrument Research Ltd laser extensometer, using two strips of retro-reflective material centred in the middle of the specimen, at a distance of 50 mm in the tension and shear tests, and 25 mm in the compression tests.

2.1. Tension tests

The specimens for the tensions tests were cut with the fibres aligned with and perpendicular to the direction of loading. The one-ply specimens are denoted by [0,90] and the two-ply specimens by $[0,90]_2$. Following Method 302 in Ref. [12], for the measurement of the tensile strength and elastic modulus of multidirectional CFRP, 20 mm wide by 200 mm long parallel edge, unnotched specimens were sandwiched between 50 mm long aluminium end tabs with epoxy resin (trade name: Araldite Precision). In accordance with Ref. [13], the tests were carried out at a strain rate of $0.2^{-3}\,\mathrm{s}^{-1}$. To achieve a more uniform distribution of stress in the fibres, each specimen was subjected to four load cycles up to about 80% of the ultimate stress, before being loaded up to failure.

2.2. In-plane shear tests

The in-plane shear modulus and shear strength were measured by carrying out tension tests [14], on one-ply $[\pm 45]$ and two-ply $[\pm 45]_2$ specimens. These properties are required to predict the compressive strength.

2.3. Compression tests

The compression tests were carried out on short sandwich columns, consisting of two CFRP face sheets bonded to a closed-cell PVC foam core, as shown in Fig. 2. Fleck and Sridhar [11] have shown that by suitable choice of the properties of the foam the lateral restraint provided by the core can be optimised to prevent failure by overall Euler

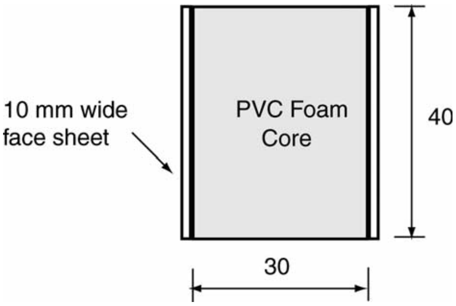

Fig. 2. Sandwich column compression specimen (dimensions in mm).

buckling, core shear macrobuckling, and face wrinkling so that the specimen fails by fibre microbuckling, which is closest to the expected mode of failure on the compression side of an ultra-thin laminate subjected to high bending strains.

Hence, the specimens were designed so that they would fail by fibre microbuckling. Having chosen a specimen width of 10 mm and length of 40 mm, and a closed-cell PVC foam for the sandwich core (trade name: Divinvycell, density 186 kg/m^3), a core depth of 30 mm was required. The face sheets were bonded to the sandwich core using Araldite Precision epoxy resin, and were cured at room temperature.

Two changes were made to the procedure in Ref. [11]. First, our specimens were significantly narrower, due to the limited availability of material. Second, steel end plates were bonded to both ends of each specimen, to minimize any stress concentrations.

2.4. Bending tests

The aim of the bending test is to determine the smallest radius of curvature that a particular specimen will survive without failing. Because of their thinness, one- and two-ply laminates can be folded to very small radii; hence, the standard three-point and four-point bending test layouts are unsuitable. An alternative layout has been devised, as shown in Fig. 3, which permits very large displacements and applies a relatively uniform bending moment and hence curvature over the centre region of a specimen that is near to failing in bending.

Specimens with a width of 15 mm were cut to a length of $\pi R_{\min}+30$ mm, where $R_{\min}$ is the estimated minimum radius of curvature, were attached with 3M79 glass tape to square rods connected to the Instron end fixings. Then, the cross-head of the Instron was driven at a rate of 0.1 mm/s, and a Sony DCR-PC110E digital video camera was used to take images of the specimen under different amounts of end shortening. Once the specimen had failed, the last few images from the movie were used to measure the radius of curvature of the specimen before failure.

Note that if the specimen is too long the rods to which it is attached will come into contact before the specimen fails. When this happens, the test has to be repeated with a shorter specimen.

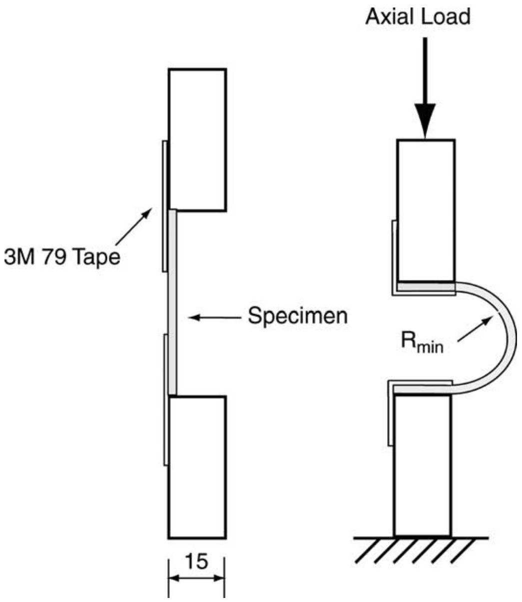

Fig. 3. Layout of bending test (dimensions in mm).

3. Experimental results

A sample plot of the measurements taken from each of the four tests described above are presented in this section.

Fig. 4 shows the stress–strain response of a particular T300/913 [0,90] specimen; note that the response is clearly linear elastic until failure, at a longitudinal strain $\varepsilon \approx 1.14\%$. The average elastic modulus parallel to the fibre direction was found to be 60 GPa for the T300/913 samples and 52 GPa for the T300/914 samples, for both one-ply and two-ply laminates. Using the material properties in Table 1, rule of mixtures estimates of 60 and 56 GPa are obtained for the T300/913 (fibre volume fraction 50%) and T300/914 (fibre volume fraction 47%) laminates, respectively.

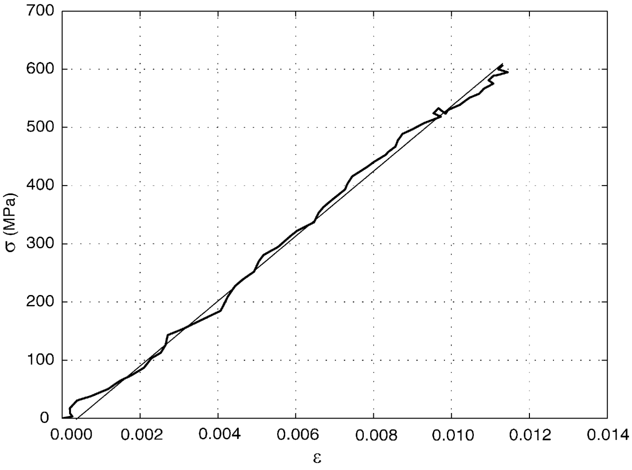

Fig. 4. Stress–strain response from tension test on one-ply T300/913.

Table 1
Properties of fibres and resins

	T300	913	914
Young's modulus, E (GPa)	230	3.39	3.9
Shear modulus, G (GPa)	8.96	1.21	1.4
Poisson's ratio, ν	0.2	0.41	0.41
Density, ρ (kg/m^3)	1770	1230	1290
Tensile strength, σ_{TS} (MPa)	3200	65.5	47.7
Compressive strength, σ_{CS} (MPa)	2000	–	180

Fig. 5 shows the behaviour in shear, which characterises the non-linear behaviour of the matrix. The average shear moduli from the experiments were 3.0 and 3.1 GPa, respectively, for T300/913 and T300/914 specimens.

Fig. 6 shows a plot of compressive stress versus strain for one of the very few compression tests in which the specimen failed by fibre microbuckling; delamination and Euler buckling due to separation from the foam core were more common failure modes. The full compressive strength of a specimen was difficult to achieve and the measured values of the compressive modulus were also rather variable, although generally higher than the tension modulus.

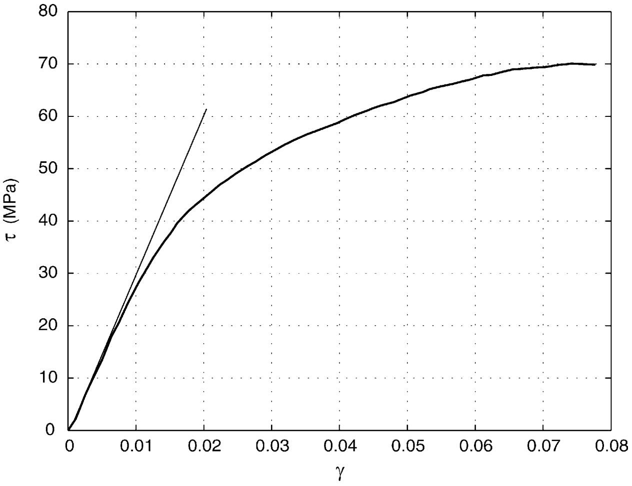

Fig. 5. Stress–strain response from in-plane shear test on one-ply T300/913.

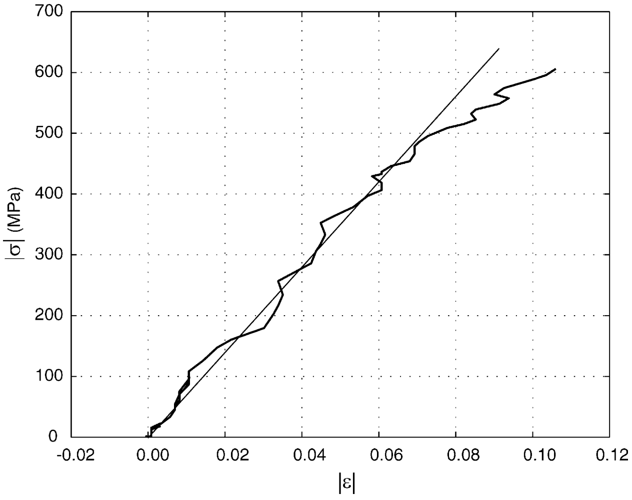

Fig. 6. Stress–strain response from compression test on one-ply T300/913.

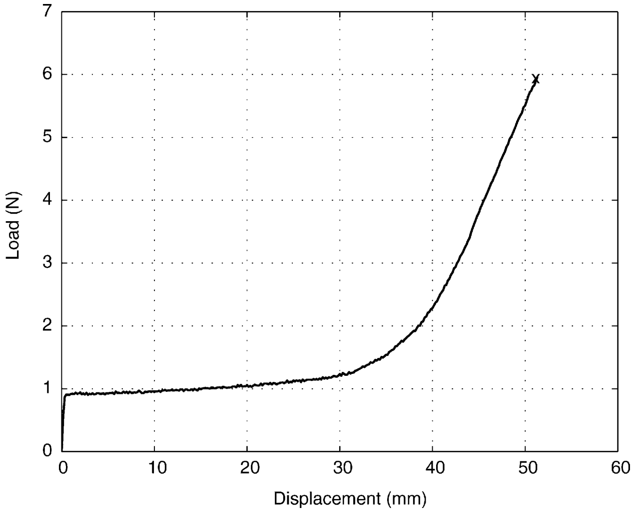

Fig. 7. Load–displacement measurements from bending test on one-ply T300/913.

Fig. 7 is a plot of the axial load versus end displacement from the bending test. This plot is not required for the calculation of the maximum bending strain (which is obtained from the digital images taken during the tests) but is an interesting example of the post-buckled response of an Euler strut that comes into contact with end attachments and thus becomes stiffer. It can be used to estimate the flexural modulus of the specimen. The maximum bending strain occurs on the outermost surface of the specimen and, given the thickness t of the specimen and the smallest radius of curvature observed in the bending test

$$\varepsilon_1 = \frac{t}{2R_{\min}} \tag{1}$$

The maximum strains derived from the tension, compression and bending tests are summarised in Table 2. Overall, the average maximum strain in tension, in the direction of the fibres, is around 1.0% when the fibres are aligned with the directions of principal strain. The average maximum strain in compression is around

Table 2
Ultimate strains along fibres

Specimen	Orientation	Tension, ε_{T} (%)	Compression, ε_{C} (%)	Bending, ε_{B} (%)
T300/913	[0,90]	1.00 ± 0.09	0.95 ± 0.12	2.71 ± 0.05
	[±45]	–	–	2.29 ± 0.02
	$[0,90]_2$	0.99 ± 0.04	0.69 ± 0.01	1.89 ± 0.09
	$[\pm 45]_2$	–	–	1.77 ± 0.03
T300/914	[0,90]	0.96 ± 0.11	0.37 ± 0.03	2.77 ± 0.02
	[±45]	–	–	2.64 ± 0.03
	$[0,90]_2$	0.92 ± 0.13	0.62 ± 0.14	2.19 ± 0.11
	$[\pm 45]_2$	–	–	1.78 ± 0.04

Table 3
Strength of laminates

Specimen	Tension, σ_T (MPa)	Compression, σ_C (MPa)	Shear, τ (MPa)
T300/913,one-ply	582.0±58.8	523.9±92.3	67.9±1.5
T300/913, two-ply	513.7±2.4	484.4±24.1	93.2±9.5
T300/914, one-ply	486.3±40.6	356.8±25.5	50.6±5.6
T300/914, two-ply	451.9±24.4	326.6±25.4	75.0±7.1

0.7%, for all specimens. The maximum bending strain in the direction of the fibres is typically 2.7% for one ply and 2.1% for two plies, when the fibres are along the directions of principal strain. When the fibres are at 45° to the directions of principal strain, which is the case when a bending test is carried out on a [±45] specimen, the maximum average fibre strain is around 2.5% for one ply and 1.8% for two plies.

Table 3 shows that the tensile strengths of T300/913 and T300/914 one-ply and two-ply laminates are similar, with average values of approximately 548 and 469 MPa, respectively. The compressive strength for one ply, though, is higher than that for two plies, and vice versa in terms of shear strength. Finally, it can be noted that overall the T300/913 specimens have performed better than T300/914.

4. Estimation of compressive strength

The measured compressive strength of one-ply specimens was predicted from the measured shear modulus. According to Ref. [15], the dominant mechanism of compressive failure in polymer-matrix composites is plastic microbuckling. Hence, the compressive strength is controlled by fibre misalignment together with plastic shear deformation of the matrix. Their compressive strength can be estimated from

$$\sigma_C = \frac{\tau_y}{\gamma_y + \bar{\phi}} = \frac{G}{1 + \bar{\phi}/\gamma_y} \tag{2}$$

where τ_y is the yield strength of the composite in shear, γ_y is the corresponding yield strain ($\gamma_y = \tau_y/G$), and ϕ is the maximum initial misalignment angle of the fibres.

Fig. 8 shows a micrograph of a one-ply specimen from which an initial fibre misalignment angle of 0.091 rad was measured. By substituting this value into Eq. (2), together with the shear modulus from Section 2.2 and the shear strength from Table 3, a compressive strength of around 428 MPa was estimated. This value correlates well with the average measured values of around 357 MPa and, considering the large scatter in the measured strength, this indicates that the full compressive strength has been captured reasonably well in the tests.

5. Discussion and conclusion

The behaviour of one-ply (respectively, 0.22 and 0.23 mm thick) and two-ply (respectively, 0.43 and 0.46 mm thick) woven T300/913 and T300/914 specimens can be described as follows.

In tension (along one set of fibres) they are linear up to failure, which occurs at an average strain of 1.0%. This behaviour is quite repeatable, the standard deviation in the maximum strain being around 9%. In compression, (also along one set of fibres) they often show a non-linear response, due to bedding-in deformation, end brooming, and delamination. The measurements of maximum compressive strain were much less repeatable, the overall average being 0.7%. In in-plane shear (at 45° to the fibres) their response is matrix dominated and hence also non-linear.

The most useful test, from the viewpoint of the application of thin composites to deployable structures, is their bending behaviour, which has been characterised by means of a large-displacement buckling test. The maximum surface strains in the direction of the fibres are around 2.8% for one-ply and 1.9% for two-ply specimens. These values were obtained for bending the specimens with the principal strain directions parallel to the fibres. Somewhat smaller maximum fibre strains, by up to 15%, were obtained for the fibres and the principal strain directions at 45°. It should be noted that—because in the latter case the major principal strain, which controls the maximum bending curvature that can be applied to a specimen, is twice the value along the fibres—all [±45] specimens can be folded to a much tighter radius than [0,90] specimens of equal thickness. Finally, it should be noted that the proposed bending test is straightforward to carry out and the measurements are very repeatable.

A comparison of one-ply and two-ply laminates, in Table 2, shows that the ultimate strains along the fibres—measured from bending tests—are on average 36% higher in

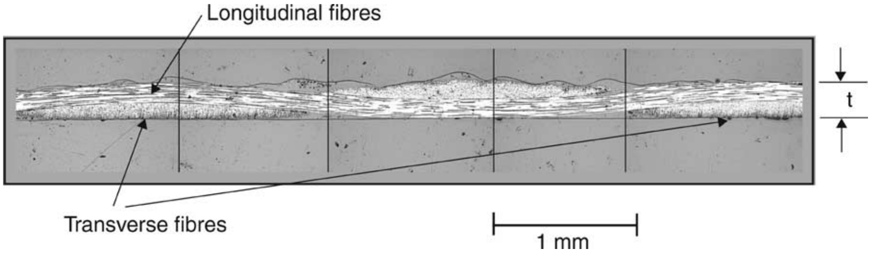

Fig. 8. Optical microscope image of microstructure of one-ply T300/914.

one-ply laminates. Generally, the maximum surface strains that have been measured in the present study are much larger than the failure strains of T300 fibres (for which Toray quote a failure strain of 1.6%).

Scaling effects could be invoked to justify these results. For example, a recent computational study, see Section 5 of Ref. [16], has shown that scaling effects rapidly increase when the ratio between specimen thickness and fibre diameter is less than 200; in the present study this ratio is in the range 40–80. However, we believe that in the present case high surface strains do not correspond to equally high peak strains in the fibres. Fig. 8 shows the cross-section of a thin specimen made from a single-ply woven fabric; note that it consists of thin and wide bundles of fibres whose thickness is, in this case, approximately half the total thickness of the specimen. If, instead of assuming that the specimen behaves as an orthotropic plate, we assume a three-dimensional grillage of beams—where each bundle of fibres forms a beam—then each beam will have to bend about its own neutral axis and so the maximum strain will be half the strain obtained from the plate model. A more detailed study along these lines is currently being completed.

Regarding the design of tightly folded regions in deployable composite structures, it can be concluded that this should be based on allowable bending strains that are either measured directly from coupon bending tests or—for preliminary design—on the values presented in this paper. Finally, with reference to the design of CFRP tape springs discussed in Section 1, the reader should be aware that the results presented in this paper apply to folding in one direction only, whereas a tape spring undergoes biaxial changes of curvature. The interaction between strains on two set of orthogonal fibres will need to be considered.

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