Compression Strength of Textile and Wavy Fiber Composites

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Summary

Compression strengths of 3-D braided, 3-D orthogonal woven, and 3-D braided with pultruded rods composites were measured. The average strength of braided, woven, and braided with pultruded rod composites was 262.7, 373.6, and 268.3 MPa, respectively. The data scatter was reasonable for woven and braided with pultruded rod composites but it was large (about ±17%) for 3-D braided composites. Micrographic studies concluded that the natural waviness of fiber tows in textile composites lead to buckling and shear kinking fracture of fibers. The tow collapse model, which incorporates this phenomenon, accurately predicted the compression strength of all three textile preform composites. The compression strength was found to be strongly dependent on the axial tow misalignment angle. The use of pultruded rods in place of axial braider tows reduced the manufacture process induced tow misalignment and hence increased the compression strength of braided composites.

Introduction

Advances have been made in laminated composite materials to build structures that are lighter, stiffer, and stronger than their metallic counterparts. Further developments are being in reducing the manufacturing cost, sometimes at the expense of performance. Textile preform composites are one such development. The interlocked fiber architecture increases the delamination resistance of the composites, but the natural waviness of fibers can significantly reduce its compression strength. Some innovative ways of selectively reinforcing composite structural components have been experimented in helicopter industries. However more studies are needed to improve the compression properties of textile preform composites. In addition, analytical compression strength models would help in understanding the influence of various parameters that contribute to the strength and developing innovative processing and fabrication techniques to improve the strength. In this direction, Shivakumar and Emehal[1,2] developed a simple compression strength model, referred to as the "tow collapse model" for multiaxial laminates and textile preform composites. This model is an extension of unidirectional fiber microbuckling (or kinking) models of Argon's[3], Budiansky[4], and Fleck and Budiansky[5]. The objective of this paper is to verify the tow collapse model

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through experimentation on 3-D triaxial braided and woven composites. Then, evaluate the use of pultruded axial rods to enhance the compression strength of textile preform composites.

Material System

The textile preform composite panels were made of BASF G30-500, 6k graphite fibers and Dow Chemicals' Tactix 123 resin. Three types of textile architecture were used, namely, 3-D braid, 3-D orthogonal weave, and 3-D braid with pultruded rods (referred to as braid with pultruded rods). In the third case, the axial tows were replaced by pultruded rods, which are straight like an arrow. Fabric architecture is designated by the orientation of the fiber tows about the load axis. Braids are represented by $0/\pm\beta$, where β is the braid angle and the weave is represented by 0/90/90. The 0 deg represent the axial direction and the two 90 deg represents the two orthogonal axis on the plane normal to the weaving direction. Flat panels of 300x300 mm were fabricated using the resin transfer molding process. Specimens of 125x19 mm and 5.5 mm thickness with 25 mm gage length were extracted for compression tests. Table 1 lists preform architecture and the fiber volume fraction (V_f) of the specimens.

Tab.1 Measured and calculated compression strength of textile preform composites

	Fiber volume fraction	Compression strength, MPa: Test data, Uncorrected	Test data, Corrected for SCF	Tow collapse model		
Braids				$6^o/\pm17^o$	$7^o/\pm17^o$	$8^o/\pm17^o$
B1	0.45	218.6	242.6	311.9	282.5	260.8
B2	0.33	235.1	261.0	232.8	211.0	194.6
B3	0.35	277.2	307.7	245.4	222.4	205.2
B4	0.41	215.8	239.5	283.2	256.6	236.8
Average	0.38	236.7	262.7	268.3	243.1	224.3
Weaves				$3^o/\pm90^o$	$4^o/\pm90^o$	$5^o/\pm90^o$
W1	0.43	367.1	414.9	482.2	374.2	309.6
W2	0.46	396.7	448.2	521.9	405.0	335.1
W3	0.42	408.3	461.4	473.2	367.2	303.9
W4	0.44	322.2	364.1	500.4	388.2	321.3
Average	0.44	373.6	422.1	494.4	383.7	317.5
Braids with pultruded rods				$2^o/\pm37^o$	$3^o/\pm37^o$	$4^o/\pm37^o$
PR2	0.25	242.4	269.1	381.2	266.1	208.7
PR3	0.35	249.5	276.9	548.6	382.9	300.3
PR4	0.25	244.2	271.1	389.0	271.5	212.9
PR5	0.26	230.7	256.1	409.1	285.6	223.9
Average	0.28	241.7	268.3	432.0	301.5	236.5

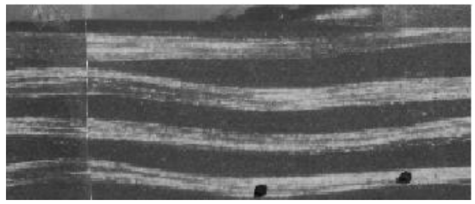
Note that the axial fiber orientation of composites was different for different types of textile architectures. Axial fiber tow orientations ranged from 6-8 deg for 3-D braids, 3-5 deg for weaves, and 2-4 for braid with pultruded rods. Note that the pultruded rod's panel was fabricated with low lateral pressure so that the rods are not broken during the fabrication. This resulted in a low fiber volume fraction (average V_f =0.28).

Tow Collapse Model

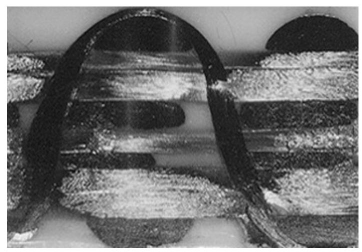
The tow collapse analysis[1,2} is an extension of microbuckling analysis of Argon[3], Budiansky[4], and Fleck and Budiansky[5] for unidirectional composites. Because of natural waviness of fiber tows in textile preform composites (see Fig. 1) and the wave angle is reasonably large no distinction is made between the misalignment and kink angles. The natural waviness is introduced during the fabric manufacturing and consolidation process. In the tow collapse model the textile composite is assumed to be an assemblage of N set of inclined fiber tows. The compression strength of the composite is the weighted sum of strengths of the N sets of fiber tows. The load carried by each set of tows is a function of tow inclination (ϕ_i) to the load, tow cross-sectional area fraction (A_i), total fiber volume fraction (V_f), transverse yield strength of the composite (σ_{tys}), and the shear yield strength (τ_{ysm}) of the matrix in the presence of fiber constraint. The expression for the compression strength (σ_c) is given by

$$\sigma_c = \left(\frac{V_f}{V_{fRef}}\right)\tau_{ysm}\sum_{i=1}^{N} A_i \sqrt{\frac{1}{\tan^2\phi_i} + \left(\frac{\sigma_{tys}}{\tau_{ysm}}\right)^2} \qquad (1)$$

The reference fiber volume fraction V_{fRef} is assumed to be 0.6 based on the linear relationship derived from Greszczuk[8] experimental data for unidirectional composites. Values of σ_{tys} and τ_{ysm} used in the present analysis were 127.6 and 63.8 MPa, respectively. The area fractions of 3-D braids were A_1=0.46, A_2=A_3=0.27, for the weaves were A_1=0.5, A_2=A_3=0.25, and for braids with pultruded rods were A_1=0.46, A_2=A_3=0.27.



(a) 3-D Triaxial braid



(b) 3-D Orthogonal weave

(c) 3-D Braid with pultruded axials

Fig.1: Sectional view of three types of textile preform architectures

Compression Test

Test Specimen

Modified IITRI test specimen[6,7] with and without tapered cross-ply glass/epoxy tabs was used in the present study. Figure 2 shows the details of the specimen configuration with two types of tabs. The specimen width was 19 mm, thickness was 5.5 mm, and the unsupported length was 25 mm. The global buckling stress for simply-supported end conditions was about 101 MPa for textile composites for G=2.8 GPa and E=55.2 GPa. This buckling stress is about three times the expected compression strength of the textile composites. All specimens were strain gaged in both the axial and transverse directions on top and bottom faces of the specimen to measure both bending and membrane strains.

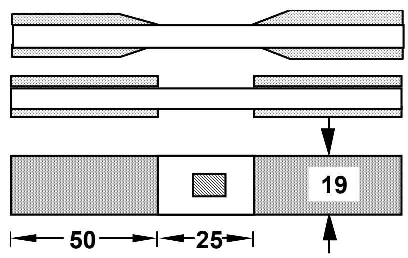


Fig.2: Test Specimen Configuration

Test Procedure

The specimens were tested in compression using the IITRI test fixture in a universal testing machine. A displacement controlled load was applied at a constant rate of 0.5 mm/minute. Stroke displacement, load, and strains were recorded at every two second interval in an automatic data acquisition system. The test was stopped immediately after the ultimate load. The ultimate load was used for calculating the compression strength of the material. During the test, the specimens were visually monitored and failure processes were monitored. After the test, the failed regions of the specimens were inspected through a microscope and the relevant areas were photographed.

Results and Discussions

Test Results

Figures 3 and 4 show stress-displacement response of 3-D braided and braided with pultruded rods specimens, respectively. Results of woven specimens were similar to that of braided composites, hence it is not shown. Almost all specimens failed by sudden fracture with little damage progression. An evaluation of back and front strain gages showed that the specimen bending was small and the bending strain was less than 10% of membrane strains immediately before the fracture. Visual monitoring of specimens during the test showed that the failure in braided specimens initiated as a surface tow buckling (out-of-plane buckling of tows) followed transverse shear fracture (see Fig. 5(a)). The buckled surface tows spanned between the two consecutive tows interlocks. The transverse shear failure can be characterized as the shear kinking of fibers or tow collapse. Unlike in braided specimens, woven and braided with pultruded rod specimens exhibited no out-of-plane buckling of surface tows. Tow kinking in woven composites is very clearly seen in Fig 5(b).

The ultimate load was used to calculate the compression strength. Table 1 lists the compression strengths of all the specimens. Examination of fractured specimens revealed that stress concentration due to tabs caused the specimens to fail near the tabs. A separate 3-D finite-element analysis of test specimens was conducted and found that the stress concentration factor (SCF) to be 1.11 for braided specimens (tapered tabs) and 1.13 for woven specimens (no taper tabs). Compression strength after applying this correction (refer to data after applying SCF) is also given in the Table 1. The average strength, after applying the SCF correction, is 262.7, 373.6, and 268.3 MPa for braided, woven, and braided with pultruded rod composites, respectively. The data scatter was ±17% in braided, (-14%/9.3%) in woven, and (-4.3%/3.2%) in braided with pultruded rod composites. The average V_f of braided, woven, and braided with pultruded rod composites were 0.38, 0.44, and 0.28, respectively. Contrary to one's expectation the strength of braided with pultruded rod composites has not improved from that of the braided composites because of its low V_f (0.28).

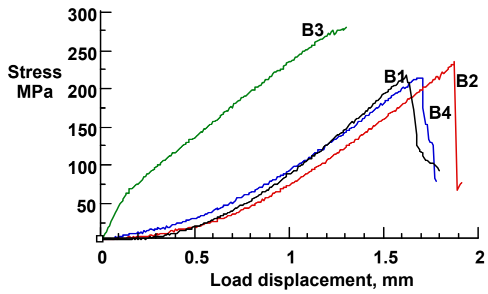


Fig.3: Stress versus displacement of 3-D braided composites

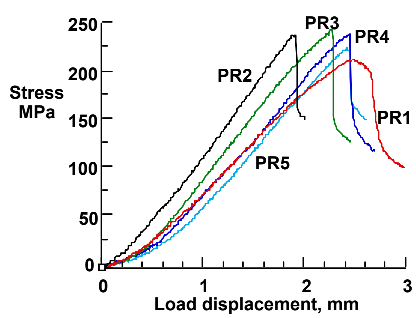
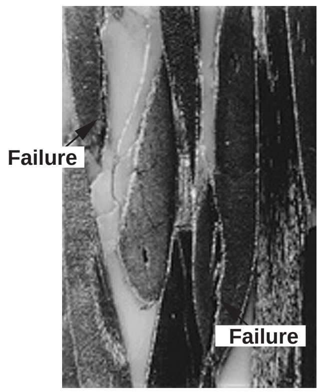
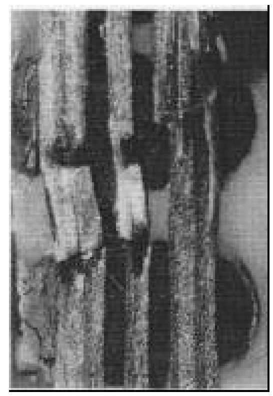


Fig.4: Stress versus displacement of 3-D braided composites with pultruded rods



(a) 3-D Braid



(b) 3-D Weave

Fig.5: Sectional view of the failed braided and woven composites

Comparison of Analysis with Test

Calculated compression strength from the tow collapse model for all three composites is given in Table 1. Because the axial tow orientation was different from specimen to specimen and location to location, calculations are made for a range of angles: 6-8 deg for braids, 3-5 deg for weaves, and 2-4 deg for braids with pultruded rods. Fiber volume fractions of respective specimens were used in the calculation. Calculated strengths for $7^o/\pm17^o$ braided, $3.5^o/90^o/90^o$ woven, and $3.5^o/\pm37^o$ braided with pultruded rod specimens agree with the respective test data. Figure 6 shows the comparison of analysis with test data for various angle of axial tow orientations. For all three composites the analytical results agree well with the test data. Because the values of V_f were different for different composites, the advantage of using the pultruded is not apparent. The figure 7 shows the normalized plot of Fig. 6. All the strengths are normalized by average V_f (0.38) of the braided composites. Normalized compression strength of braid with pultruded rod composites is 327.1 MPa about 38% larger than the bare 3-D braids (262.7 MPa). This strength increase is attributed to smaller misalignment angle of pultruded rods. It is apparent from the tow collapse model equation that the lower misalignment angle gives higher compression strength of braided composites. Therefore, the use of pultruded rods as axial tows can increase the compression strength. Noted here that any process modification to increase V_f might change the axial tow orientation. In the case of woven composites, because the axial tows were held in tension during weaving, it had the lower misalignment angle. Finally, the tow collapse model has all the important parameters to predict the compression strength of textile composites.

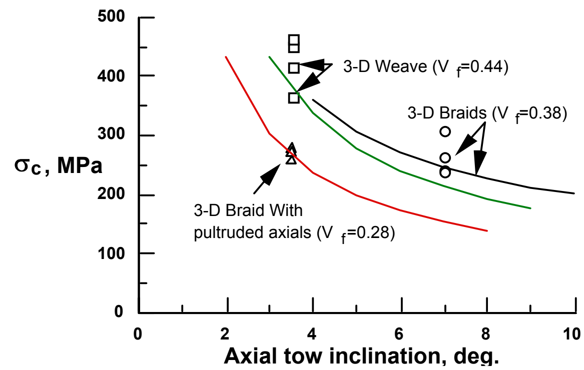


Fig.6: Comparison of predicted and experimental compression strength

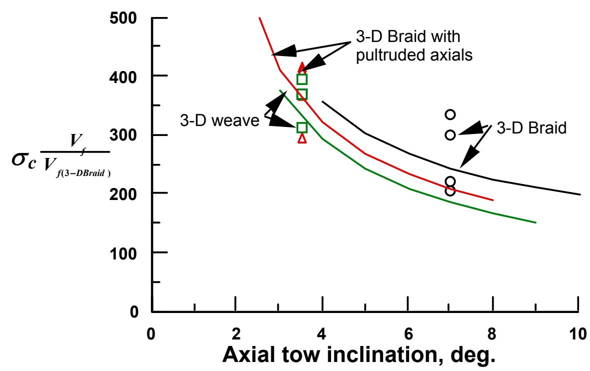


Fig.7 Normalized compression strength of the three composites

Concluding Remarks

Three types of textile preform composites were made from BASF G30-500 6k graphite yarns and Dow Chemicals Tactix 123 matrix, using a resin transfer molding technique. The preform architectures were 3-D braid ($7^o/\pm17^o$), 3-D orthogonal weave ($3.5^o/90^o/90^o$), and 3-D braid with pultruded rods ($3.5^o/\pm17^o$). In the last preform the axial tows were replaced by pultruded rods. Compression tests were conducted using the IITRI test fixture. The average compression strength of braided, woven, and braided with pultruded rod composites was 262.7, 373.6, and 268.3 MPa, respectively. The data scatter was reasonable for woven and braided with pultruded rod composites but it was large (about ±17%) for 3-D braided composites. Micrographic studies concluded that the natural waviness of fiber tows in textile composites lead to buckling and shear kinking fracture of fiber tows. The tow collapse model, which incorporates this phenomenon, accurately predicted the compression failure of all three textile preform composites. The compression strength was found to be strongly dependent on the axial tow misalignment angle. A small variation in the axial tow orientation can have a significant change in the compression strength. Braid with pultruded rods had small misalignment angle, consequently it had high compression strength. Similar trend was noticed also in woven composites, wherein the axial tows were held in tension during the weaving. Therefore the use of pultruded rods in place of axial tows can improve the compression strength of braided composites.

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