FAILURE ANALYSIS OF BIAXIAL BRAIDED COMPOSITES UNDER FATIGUE LOADING

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Abstract

This research addresses failure analysis of vacuum assisted resin transfer molding (VARTM) manufactured carbon/epoxy biaxial braided composites under load controlled tension-tension fatigue loading. The fatigue stress is applied as a percentage of ultimate tensile strength. It is observed that the ultimate tensile strength is a function of the braid angle and fiber volume percentage. The variation in the ultimate tensile strength between the specimens causes relatively large scatter in the fatigue data. The scatter is confirmed on S/S_u-N diagram and on stiffness degradation diagrams. A simple statistical approach is proposed to predict the ultimate tensile strength of braided composites using braid angle and fiber volume percentage of the composites.

Background

The Federal Aviation Administration (Part 23 Single Pilot Certification) requires a take-off weight of 5670 kgf (12,500 lb) or less. Typically, small business jets have a seven-passenger capacity; maximum cruise speed of 853 kmph (465 knots or 530 mph) and a maximum range of 3000 km (1875 miles). The major objectives in the small business jet industry are to reduce costs while keeping weight below 5670 kgf (12,500 lb). Reduced weight is possible only if the primary and secondary structures are made of lightweight composite materials. Thus, competitive costs depend on the selection of fabric, resin, and manufacturing methods. The main design feature of small business jets today is a composite fuselage built with automated fiber placement techniques.

Biaxial braided fabric with its natural conformability can fit over any complex shape. Thus, there is no need for cutting, stitching, and fiber placement as required for woven fabric. This ability reduces part count and makes biaxial braided fabric useful for primary structures like fuselage. Braided composites are proven to be cost competitive by cost analysis. It was recently shown that the carbon braids are extremely efficient for single-part airfoil sections like wing flaps (Swain [1]). Vacuum assisted resin transfer molding (VARTM) is a low-cost manufacturing process with the capability of manufacturing complex parts with higher fiber volume percentages than those from hand lay-up. Braided composite manufactured using the VARTM process is one of the major candidates for small business jet applications. Before the braided composites can be confidently used in the primary structures, it is necessary to understand the performance of biaxial braided composites under various loading conditions. This research focuses on the performance of the braided composites under tension-tension fatigue loading.

Biaxial Braids

The tube form is the most popular form of braided fabric. The tube form is available in two architectures biaxial and triaxial as shown in the Fig. 1. Braid architecture resembles a combination of filament winding and weaving. Fibers in braid tubes have continuity between the ends of the part, and they are mechanically interlocked. Biaxial braid tubes have natural conformability, also referred to as 'Chinese Finger Trap', which refers to the diameter reduction when the tubes are pulled along lengthwise. Braid tube fits on complex components with ease just like pulling socks on feet. Therefore, cutting, stitching, and fiber placement are not required as in woven fabric. The introduction of axial yarn in triaxial braid locks the diameter and stops the braid's natural conformability.

Biaxial braids are classified as diamond braid (1/1), regular braid (2/2), and Hercules braid (3/3) depending on the interlacement. The braid tubes are specified at $\pm 45°$ orientation. Fiber orientation is the angle measured from the axis of the braid to the axis of the bias yarns. This angle is also called the "braid angle" or the "fiber angle" or the "bias angle" and usually denoted by θ (Fig. 1). Fiber orientation typically ranges from 15° to 75°. When a biaxial braid tube is used for a component of varying cross-sections, the braid angle, thickness, and areal weight (yield) vary from point to point.
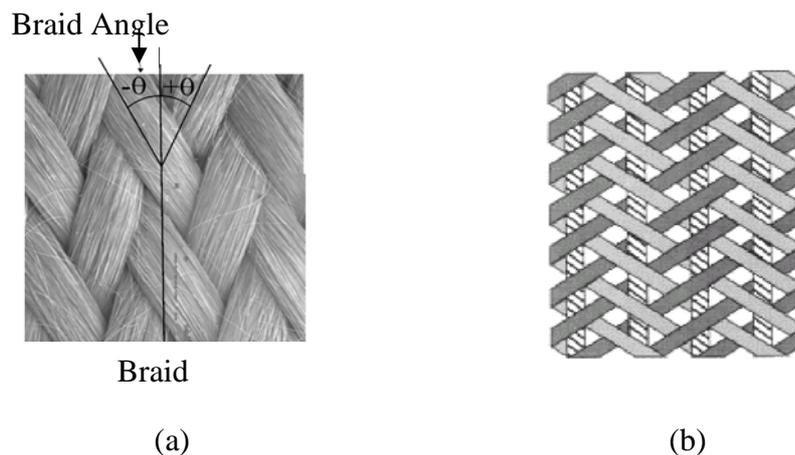
Braid Angle

$-\theta$ $+\theta$

Braid

(a)

(b)

FIGURE 1. (a) Biaxial braid (b) Triaxial braid (Byun, 2000)

Advantages of Braided Composites

1. Braided structures are impact resistant. Since all the fibers in the structure are involved in the load distribution, the braid absorbs a large amount of energy as it fails. These braids are used in fan blade containment in commercial aircraft and energy absorbing crash structures in Formula One racing cars.
2. Since braids are woven on the bias, they provide very efficient reinforcement for parts that are subjected to torsional loads such as drive shafts.
3. Braided composites have better fatigue life. They have outperformed unidirectional laminates for jet engine stator vanes in fatigue strength (A & P Technology, Inc., http://www.braider.com/index_hi.html).

4. Braided composites greatly improve interlaminar shear properties. There is virtually no delamination observed when braided composites are subjected to fatigue loadings (Kelkar and Tate [2], [3]).

5. It has been proven that braiding can be used to improve performance and reduce the manufacturing cost of composite structures. Braiding has been compared with other manufacturing methods such as filament winding, manual and automated tape lay-up, roll wrapping (tape winding) and pultrusion in terms of versatility, component reproducibility, composite quality/structural integrity, design flexibility, damage tolerance, repairability, microcracking resistance, joints/attachments, resistance to thermally induced twist, and lower manufacturing costs (Munjal and Maloney [4]).

VARTM Fabrication Process

VARTM is a single/double sided tooling process where a dry preform is placed into the tool and vacuum bagged in conjunction with resin distribution and vacuum distribution lines. A low viscosity resin is drawn into the preform through the aid of vacuum. In VARTM process, the flow of resin occurs in plane as well as in the transverse directions to the preform. The permeability of the preform, fiber architecture and fabric crimp has an influence on the wetting of the fabric. This process is being currently used in many of the applications in the general aviation industry, defense sector and in the transport industry. The schematic for the fabrication is shown in the Fig. 2.

This process has certain advantages as listed below:
- Relatively low cost for high volume production
- Simple low cost tooling
- Very large and complex parts are practical
- High fiber volume percentage than hand lay-up
- On site manufacturing and repairing is possible
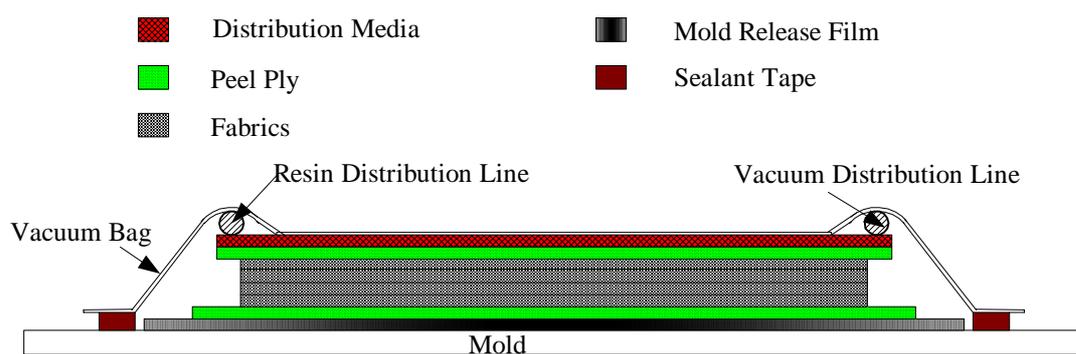- Reduced environmental concerns than hand lay-up as it is closed system

FIGURE 2. Schematic for VARTM

Objectives

(a) To fabricate 2 x 2 biaxial braided composites using the VARTM manufacturing process
(b) To perform displacement controlled static tension tests (ASTM D3039)
(c) To develop statistical model to predict ultimate tensile strength as a function of a braid angle and fiber volume percentage

(d) To perform load controlled tension-tension fatigue tests (ASTM D3479)
(e) To develop S/Su-N diagram

Material System

The braided composites were manufactured using 2 x 2 biaxial carbon (AS4) braid tubes and slit sleeves manufactured by A & P Technology, Inc. The resin system used is EPON 9504 manufactured by Resolution Performance Products, Inc.

Braided composites with braid angle of 25° were manufactured using braid tubes. It was observed that a braid tube with a width of 44.5 mm (1.75 in) provided a braid angle of ~25°. Two tubes were collapsed and then were stacked above each other, creating four layers. This method was referred to as a 'collapse method.'

Braided composites with braid angle 30° and 45° were manufactured using slit sleeves. Slit sleeve is special product that maintains constant braid angle throughout the fabric. Braid tubes are cut along the braid axis and the edges are fused to create slit sleeves. Four slit sleeves were stacked above each other to obtain four layers.

Static Tension and Tension-Tension Fatigue Tests

Static tensile tests were performed according to ASTM D3039. The in-plane tensile properties such as ultimate tensile strength (UTS or, S_u), strain at UTS, longitudinal tensile modulus, and Poisson's ratio were evaluated using this standard. The axial extension was measured by an extensometer and transverse strain was measured by a strain gage. All static tensile tests were conducted in the displacement control mode with a crosshead rate of 1.27 mm/min (0.05 in/min).

Tension-tension fatigue tests were performed according to ASTM D3479. The unnotched test specimens were subjected to constant amplitude uniaxial in-plane loading that was defined in terms of a load. The fatigue stress was applied as percentage of ultimate tensile strength (UTS).

Tensile stress was applied from 80% of UTS and reduced in steps of 10% until specimens survived 1 million cycles. In the present research, endurance limit refers to the stress level for which specimen lasted at least 1 million cycles. The other test parameters selected were sinusoidal waveform, 10 Hz frequency, and 0.1 stress ratio (R).

Results and Discussion

VARTM process has limitation that, the thickness of panel varies from resin line to vacuum line. In properly manufactured VARTM panels it is observed that, thickness variation is ±10% and fiber volume percentage varies from 46% to 56% within the panel. Braided composites manufactured using braid tubes exhibited ±2° braid angle variations within the panel, whereas braided composites manufactured using slit sleeves exhibited ±1° braid angle variation within the panel. Typically 10 to 12 specimens are cut from the panel.

The overall fiber volume percentage in the carbon/epoxy braided composites (braid angle 25±2°) was 51±5%. Table 1 lists the results of tensile tests for five specimens. The s represents the sample standard deviation, and CV is the sample coefficient of variation in percentage terms. E_x was computed based on a linear regression fit to the stress-strain data over the 0.1% to 0.3% strain range. Experimental error was calculated using the student t-distribution at a confidence level of 95%. The experimental error in UTS was quite

significant. As fatigue tests were based on the average value of UTS, the large scatter was expected in the fatigue data.

TABLE 1.Tensile test results of Carbon/Epoxy braided composites (Braid angle 25±2º)

Specimen	UTS		E_x		% ε_{ut}	ν_{xy}
	MPa	ksi	GPa	Msi		
Average	660.03	95.74	54.26	7.87	1.77	1.44
s	43.53	6.314	5.46	0.792	0.263	0.027
CV	6.60	6.60	10.06	10.06	14.85	1.88
Experimental Error	±54.04	±7.84	±6.78	±0.98	±0.33	±0.03

It was assumed that the properties in Table 1 represented the entire panel (lot). Fatigue tests were conducted to obtain the stress level at 1 million cycles. The test parameters were those explained in the previous section. Three specimens were tested at each stress level. The fatigue test data is tabulated in Table 2.The stress-fatigue life diagram (S/S_u–N) is displayed in Fig. 3(a). The fatigue data represented large scatters as expected.

The scatter in fatigue data in load controlled fatigue tests was due to the large experimental error in UTS. The error in UTS was mainly due to the heterogeneity of the material as opposed to the tensile test itself. This error was mainly due to braid angle and fiber volume percentage variation between the specimens. Increasing the sample size and studying the repeatability of the manufacturing process and material behavior can reduce this error.

VARTM process mainly uses pressure differential between incoming resin and vacuum in the bag, as a driving force for resin impregnation. The thickness variation within panel and in turn fiber volume percentage variation is evitable. There is very little scope in controlling the thickness in VARTM processing. The braid angle variation of ±2º within a panel was also significant in case of braid tubes. Therefore, it is highly recommended to use slit sleeves instead of braid tubes while manufacturing biaxial braided composites. When tension-tension fatigue tests were performed using slit sleeves with braid angle of 45º, the scatter in the fatigue data was negligible as shown in Fig. 3(b). The effects of braid angle and fiber volume percentage on UTS can be analyzed by using statistical linear regression analysis as explained in the following section.

TABLE 2. Fatigue test results for Carbon/Epoxy braided composite(Braid angle 25±2º)

% of UTS	Specimen 1	Specimen 2	Specimen 3
80	516	434	274
70	986	693	839
60	5575	2258	1225
50	4807	4372	3470
45	24135	1000000*	1000000*
40	1000000*	1000000*	1000000*

*Run-out
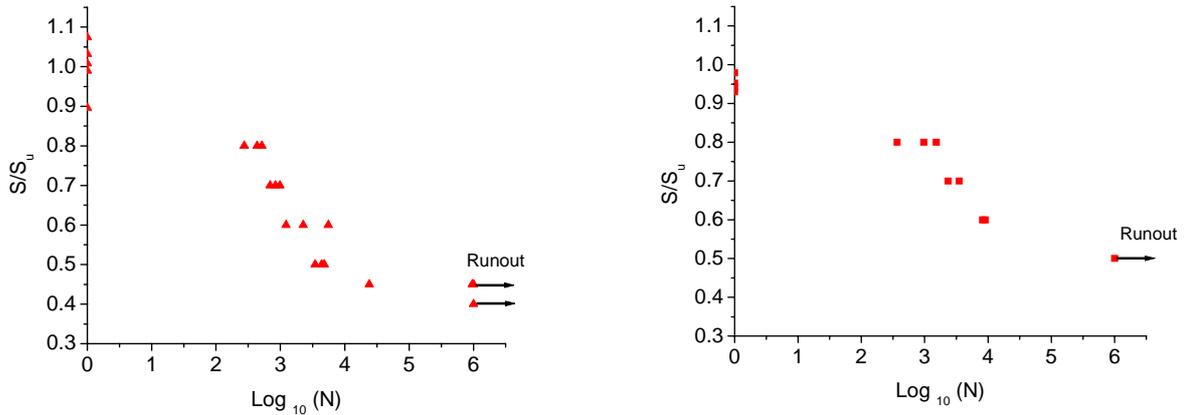

FIGURE 3. S-N Diagram for braided composites using braid tubes and slit sleeves
  (a) Large scatter in the fatigue data (Braid angle 25 ±2º)
  (b) Negligible scatter in the fatigue data (Braid angle 45 ±1º)

Statistical Analysis

It is recommended to measure the average fiber volume percentage and the average braid angle (negligible variation of braid angle within a specimen), on each specimen before tabbing. The fiber volume percentage can be measured very easily by the density method. Braid angle, can be measured on micrographs using special software like 'Image-Pro'. The relation for UTS as a function of the fiber volume percentage and the braid angle can be evaluated using statistical analysis. The equation for the UTS can be written in the form, $UTS = \beta_0 + (\beta_1 * \theta) + (\beta_2 * V_f) + (\beta_3 * \theta * V_f)$ where,

θ = Braid angle

V_f = Fiber volume percentage

$\beta_0, \beta_1, \beta_2,$ and β_3 = Parameters in linear regression model

   Once this relation is established it should be used in load controlled fatigue tests. Fiber volume percentage and braid angle, of each fatigue test specimen should be measured before tabbing. Using the above relation, UTS of each individual specimen should be computed. The stress should be applied as a percentage of this computed UTS. Figure 4 shows the flow chart of the recommended procedure.

   Total five specimens were tested in static tension with braid angles ranging from 23.8º to 26.2º. There was negligible variation of braid angle within a specimen. The requirement of the thickness tolerance within a specimen (±4%) of ASTM standard automatically controls the variation of fiber volume percentage within a specimen. The tensile tests on neat resin coupons of EPON 9504 exhibited average UTS of 64.94 MPa (9.42 ksi). This UTS value was considered as one reading with zero fiber volume percentage and zero braid angle. The linear regression analysis was performed on these six readings (Table 3) using software SAS® to establish the relation for UTS as a function of braid angle and fiber volume percentage. The statistical parameters $\beta_0, \beta_1, \beta_2,$ and β_3 were evaluated as 9.42, 5.18623, 3.28285, and –0.16943, respectively. Increasing the number of data points and incorporating braid angle variation within a specimen can improve the accuracy of the statistical analysis.

Table 3. Effect of braid angle and fiber volume percentage on UTS

Specimen Number	Average Braid Angle	Average Fiber Volume Percentage	UTS, MPa (ksi)
1	0.0	0	64.94 (9.42)*
2	26.2	49	591.50(85.80)
3	25.1	46	653.41 (94.78)
4	25.0	51	665.62 (96.55)
5	24.9	47	681.00 (98.78)
6	23.8	54	708.70 (102.80)

*This value refers to the average UTS of neat epoxy resin coupons.

Conclusions

The present study indicates that when braided tubes (collapse method) are used, there is a variation of braid angle within a specimen and also among the specimens. Furthermore, low cost manufacturing such as VARTM results into large variation of fiber volume percentage (due to thickness variation) within the panel. Thus, there exists a variation in the fiber volume percentage among the specimens. These variations in braid angle and fiber volume percentage among the specimens can result into significant scatter in the fatigue data. One way to alleviate this problem is to use sleet sleeves where at least braid angle can be controlled. However, in the real life aerospace applications, control of braid angles and fiber volume percentages may not be feasible. Hence, an alternative method based upon the statistical approach can be effectively used to minimize the scatter in the fatigue data. This method involves finding four statistical parameters, which takes into account the variation in the UTS due to variation in braid angle and fiber volume percentage among the specimens (negligible variation within a specimen). Using these parameters the UTS can be predicted and should be used to perform the fatigue experiments on the braid.
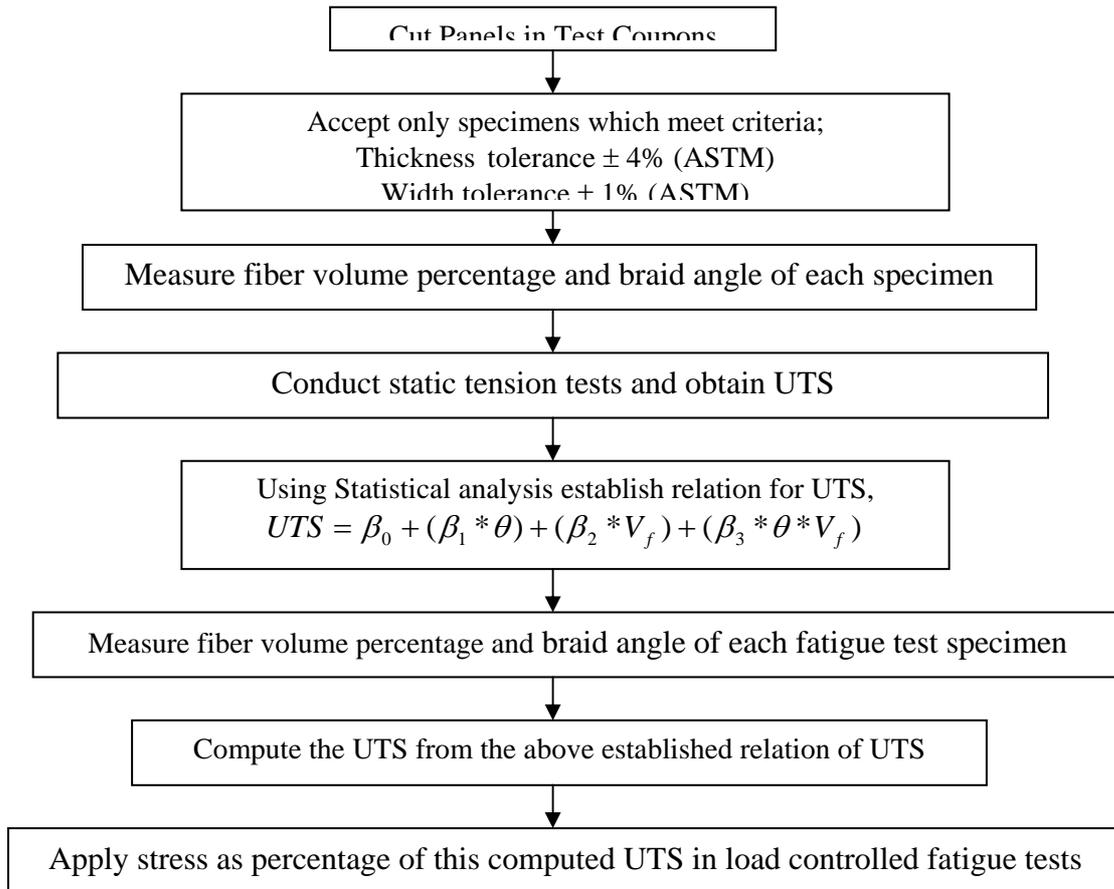
Cut Panels in Test Coupons

Accept only specimens which meet criteria;
Thickness tolerance ± 4% (ASTM)
Width tolerance ± 1% (ASTM)

Measure fiber volume percentage and braid angle of each specimen

Conduct static tension tests and obtain UTS

Using Statistical analysis establish relation for UTS,
$$UTS = \beta_0 + (\beta_1 * \theta) + (\beta_2 * V_f) + (\beta_3 * \theta * V_f)$$

Measure fiber volume percentage and braid angle of each fatigue test specimen

Compute the UTS from the above established relation of UTS

Apply stress as percentage of this computed UTS in load controlled fatigue tests

FIGURE 4. Flow chart for load controlled fatigue tests of braided composites

References

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