DETERMINATION OF CROSS-PLY LAMINATE STACKING SEQUENCE FOR THE COMPRESSION STRENGTH TESTING OF A UNIDIRECTIONAL BORON EPOXY MATERIAL

Submitted to SAMPE Fall Technical Conference – Dallas, November 6-9, 2006 Dallas, TX

Yeow Ng
National Center for Advanced Materials Performance (NCAMP)
National Institute for Aviation Research (NIAR)
Wichita State University
Wichita, KS 67260

Al Kumnick
Specialty Materials Company
Lowell, MA 01851

ABSTRACT

An experimental approach is described to optimize the stacking sequence of 0° and 90° plies in compression test specimens such that the compression strength of a unidirectional 50 volume percent boron epoxy composite can be determined. The compression strength test method is ASTM D6641 Standard Test Method for Determining the Compressive Properties of Polymer Matrix Composite Laminates Using a Combined Loading Compression (CLC). All the laminates consisted of 0º and 90º unidirectional plies with different ratios of 0° to 90° plies and varying stacking sequences. The percentage of 0º plies was varied from 50% to 10%. Equations in MIL-HDBK-17 were used to derive the 0º compression strength from the test results. The strength values obtained from this approach are among the highest and most consistent ever recorded for a unidirectional boron epoxy composite. This approach may also be used to determine the ideal stacking sequence for the compression strength test of other composite materials, such as unidirectional carbon epoxy composite materials.

KEY WORDS: Testing/Evaluation, Boron Fiber Composites

1. INTRODUCTION

The compression testing of unidirectional composite materials is one of the most difficult to perform despite many recent developments in test methods. Proper load introduction and buckling issues are just two of the problems encountered. Of all the advanced composite materials, boron epoxy is arguably the most difficult material to test for compression strength due to its very high strength, which is estimated at over 3,500 MPa (508 ksi) at room temperature. Boeing modified ASTM D695 Standard Test Method for Compressive Properties of Rigid

Plastics, which is also known as SACMA SRM 1 Compressive Properties of Oriented Fiber-Resin Composites, has traditionally been the preferred test method for boron epoxy. Samples are all 0° plies with tabbed ends. The results often have large scatter and are not easily reproduced by different operators or laboratories. A number of ASTM D695 types of test have been performed on boron epoxy and the values have ranged from 2,000 MPa (290 ksi) to over 3,300 MPa (480 ksi) depending on the sample batch and where the testing was done.

More recently ASTM D6641 Standard Test Method for Determining the Compressive Properties of Polymer Matrix Composite Laminates Using a Combined Loading Compression (CLC) has advanced and addresses some of the above issues. With cross-ply configuration specimens and back-out factors, the results are more consistent and higher, ranging from 2,800 MPa (406 ksi) to 3,500 MPa (508 ksi). A robust test method that is less dependent on operator skill which can consistently and accurately obtain the compression strength of the boron epoxy material is highly desired for material characterization and quality control purposes.

The use of ASTM D6641 Standard Test Method for Determining the Compressive Properties of Polymer Matrix Composite Laminates Using a Combined Loading Compression (CLC) with cross-ply laminates and BF has been shown to be an effective and repeatable approach to improve the accuracy of compression strength determination. Cross-ply laminates contain plies that are oriented in both 0º and 90º directions (1). The bi-directional reinforcement makes the specimens more robust (i.e. less fragile) compared to an all 0º laminate. The robustness of cross-ply laminates has been demonstrated by the low coefficient of variation obtained by various investigators (2-4). The strength of a cross-ply laminate in the fiber direction is lower than an all 0º laminate because 90º plies are weaker than 0º plies. The combination of increased robustness and lower strength makes cross-ply laminates easier to test and test results are more repeatable and reproducible.

The use of back-out factor (BF) allows the strength of 0º unidirectional lamina to be calculated from cross-ply laminate strength using "reversed" classical laminate theory. Since strength calculation involves the failure of 0º unidirectional plies, it is natural that failure theory be used with the BF approach to obtain the failure strength of the 0º unidirectional lamina (5). In this experiment, maximum stress failure theory is used with the assumption that the 90º plies continue to carry load until the failure of the 0º plies. Failure of the 0º plies causes total laminate failure because the remaining 90º plies are unable to carry the load.

2. APPROACH

ASTM D6641 (CLC) was chosen for this experiment. It requires very simple rectangular specimens without tabs. The test fixture allows users to adjust clamping force through the bolt torque. The appropriate bolt torque and the one used throughout this experiment is 10.2 to 11.3 N-m (90 to 100 in-lb). The bolt torque was chosen to prevent end blooming of the strongest specimens, namely laminate configuration 1 in Table 1.

Cross-ply laminates with 0º and 90º plies were chosen for both ease of construction and simplicity of analysis. The BF equation for laminates that contain other than 0º and 90º plies are more complicated because of the shear coupling terms. The shear stress-strain response which is often non-linear may violate the linear assumption of the classical lamination theory used to derive the BF equation.

There are three objectives in this experiment. The first objective is to determine the ideal stacking sequence for the compression strength testing of a unidirectional boron epoxy material. The second objective is to determine the true compression strength of the unidirectional boron epoxy material. The third objective is to demonstrate the method of determining suitable stacking sequence for any given unidirectional composite material.

Prior to this experiment, the authors have observed that the data scatter, which is usually measured by coefficient of variation (CV), is typically lower for laminates with lower percentage of 0º plies. The lower CV may be explained by the insensitivity to minor fluctuations in specimen quality or testing skill. The laminates with lower percentage of 0º plies will also yield higher 0º unidirectional lamina strength because the 90º plies adjacent to the 0º plies tend to prevent the 0º plies from micro-buckling (2). As the percentage of 0º plies is reduced, the true compression strength of 0º plies is being approached. In this experiment, the percentage of 0º plies is varied from 50% to 10% with some variation of stacking sequence, as shown in Table 1. The specimen thickness was designed to preclude Euler column buckling. The laminate configurations in Table 1 were designed to obtain the true compression strength of the boron epoxy material, knowing full well that the true compression strength will not be achieved in commonly used laminates (i.e. typical laminate stacking sequence in aerospace applications) where higher percentage of 0º plies are often used and micro-buckling is an evident failure mode in compression.

TABLE 1. LAMINATES STACKING SEQUENCE

Configurations	Stacking Sequence	% 0º plies
1	[90/0/90/0/90/0/90/0/90/0]S	50
2	[90/0/90/0/90/0/90/0/90/90]S	40
3	[90/0/90/0/90/0/90/90/90/90]S	30
4	[90/0/90/0/90/90/90/90/90/90]S	20
5	[90/0/90/90/90/90/90/90/90/90]S	10
6	[90/90/0/90/90/0/90/90/0/90]S	30
7	[90/90/0/90/90/0/90/90/90/90]S	20
8	[90/90/0/90/90/90/90/90/90/90]S	10

The 0º lamina compression strength, $F^{cu}_{0^\circ plies}$, was calculated using the following BF equation:

$$F^{cu}_{0^\circ plies} = BF\,\frac{P^{f}}{wh} \quad [1]$$

$$BF = \frac{E_1\left[V_0 E_2 + (1-V_0)E_1\right] - (\nu_{12} E_2)^2}{\left[V_0 E_1 + (1-V_0)E_2\right]\left[V_0 E_2 + (1-V_0)\, E_1\right] - (\nu_{12} E_2)^2} \quad [2]$$

Where BF = Back-out factor obtained using linear classical lamination theory
P^f = Peak load carried by the test specimen (usually at failure)
w = specimen gage width, mm [in.]
h = specimen gage thickness, mm [in.]
V_0 = fraction of 0° plies in the cross-ply laminate
E_1 = axial compression stiffness of 0° plies
E_2 = transverse compression stiffness of 0° plies
ν_{12} = major Poisson's ratio of 0° plies

3. EXPERIMENTAL RESULTS

TABLE 2. SUMMARY OF TEST RESULTS

Configuration (% 0º plies)	BF	Actual panel thickness, mm (inch)	Laminate strength, MPa (ksi)	CV (%)	0º lamina strength, MPa (ksi)
1 (50)	1.810	2.855 (0.1124)	1,374 (199.3)	10.5	2,487 (360.7)
2 (40)	2.159	2.781 (0.1095)	1,358 (197.0)	4.8	2,932 (425.3)
3 (30)	2.673	2.611 (0.1028)	1,084 (157.2)	3.4	2,897 (420.2)
4 (20)	3.508	2.847 (0.1121)	1,093 (158.5)	2.5	3,834 (556.1)
5 (10)	5.104	2.654 (0.1045)	715.7 (103.8)	2.4	3,652 (529.7)
6 (30)	2.673	2.753 (0.1084)	1,220 (177.0)	2.5	3,261 (472.9)
7 (20)	3.508	2.766 (0.1089)	1,042 (151.2)	2.7	3,657 (530.4)
8 (10)	5.104	2.776 (0.1093)	709.5 (102.9)	5.2	3,621 (525.2)

All the strength results in Table 2 were normalized to 50% fiber volume fraction. Despite the fiber volume fraction normalization, the actual panel thickness has a rather significant effect. Higher thickness generally yielded higher 0º lamina strength, as seen in laminate configuration 4. The variation in panel thickness is due to panel fabrication technique being altered and improved during the panel fabrication process.

The 0° compression strength increases with decreasing percentage of 0º plies (see Figure 1) and reaches a maximum at about 20% of 0º plies. No significant change occurs when the 0º plies are reduced from 20% to 10% and the results are independent of stacking sequence. The maximum value is approximately 3650 MPa (530 ksi) which represents the true compression of a 0° lamina. Although laminates with 10% of 0º plies and 20% of 0º plies both produce equal strength values, laminates with 20% 0º plies should be preferred because the BF value is smaller. BF is a multiplication factor that can magnify the scatter. Consequently, a smaller BF value should be preferred as long as accurate strength values may be obtained.

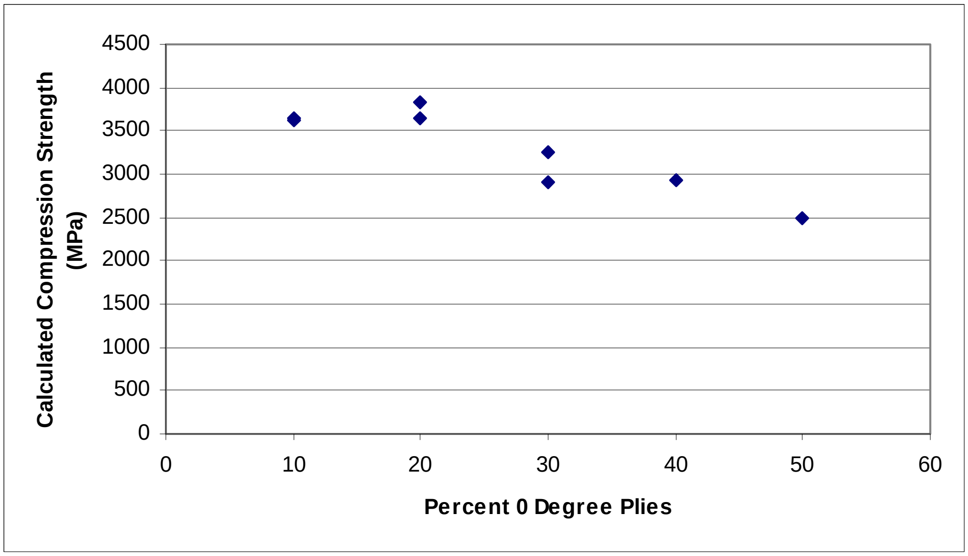

Figure 1. Relationship between Calculated Compressive Strength and Percentage of 0º Plies

4. CONCLUSIONS

A general method of determining an optimal ply orientation and stacking sequence with 0° and 90° plies for compression testing composite materials has been presented. The estimated true compression- strength of unidirectional boron epoxy which is used as an example of the analysis is about 3,650 MPa (530 ksi). The results have low data scatter with a CV of 2% as compared with those from ASTM D695 test method which have an average CV of about 7%. The results suggest that the ideal fiber volume is about 20% and more than one stacking sequence is viable (configuration 4 or 7). The use of 0°/ 90° cross-ply stacking sequences leads to more consistent test results by minimizing the effect of artifacts due to such things as sample preparation or misalignment. Calculation of the compression strength using a cross-ply configuration and BF results in more consistent and higher values than are possible with a 100%, 0° configuration.

The compression strength determined in this experiment is the highest ever reported for boron epoxy. The approach demonstrated in this experiment is well suited for material characterization and quality control purposes where accuracy and low data scatter are desired. The use of this approach for design purposes will require further study and refinement to establish appropriate knockdown factors for real world structures. The approach presented is also useful to determine the proper cross-ply laminate stacking sequence and ratio of 0° and 90° plies for other materials as well, such as carbon fiber epoxy and glass fiber epoxy materials.

Submitted to SAMPE Fall Technical Conference – Dallas, November 6-9, 2006 Dallas, TX

5. REFERENCES

1. D.F. Adams, "Testing cross-ply vs. unidirectional composites," High Performance Composites, March 2006
2. D.F. Adams, "Back-out factors," High Performance Composites, May 2006

3. L.J. Hart-Smith, March 9-12, 1992, "Backing Out Equivalent Unidirectional Lamina Strengths from Tests on Cross-Plied Laminates," 37th International SAMPE Symposium, pp. 977-990.
4. U.S. Department of Defense, 2002, *MIL-HDBK-17-1F Polymer Matrix Composites, Volume 1: Guidelines for Characterization of Structural Materials*, Washington, D.C. 20025
5. Y. Ng, "Deriving Composite Lamina Properties from Laminate Properties Using Classical Lamination Theory and Failure Criteria," Journal of Composite Materials, Vol. 39, No. 14/2005