A Discussion of Cross-ply Compression Test Results for Hy-Bor® Boron/Carbon/Epoxy Composite Material

Historical database information on the compression properties of boron fiber reinforced composite material was primarily based on testing of 0^o fiber orientation laminates using either sandwich beam 4-point bend testing (ASTM D5467) or axially-loaded test techniques. The earliest of the axially loaded techniques (ASTM D695) employed direct end-loading of a flat, untabbed specimen with a simple clamped support to the majority of the specimen length for the prevention of column buckling. This technique was quickly replaced by wedge grip shear introduction of compressive loading (ASTM 3410), commonly referred to as Celanese and IITRI (Illinois Institute Technology Research Institute) test fixtures. Specimens are configured with long end-tabs and relatively short test sections. The average data generally reported for 4-mil boron/5505 Epoxy unidirectional laminates using these techniques was 360 ksi (2485 MPa).[1]

The development of hybrid boron and carbon fiber epoxy prepreg (Hy-Bor®) configurations designed to enhance the compressive performance of structural carbon/epoxy composites has led to increased compression testing requirements for new database generation. The hybrid preform system is a high performance material with exceptional properties (see **Hy-Bor Prepreg Tape** tab). Hy-Bor material can be tailored by altering the spacing of the boron fiber in the prepreg, as well as the carbon fiber type and matrix resin system. Properties for variations in carbon tape systems are presented in a table under the **Hy-Bor Properties vs. Standard Preforms** tab.

Bell Helicopter Textron testing of 0^o laminate Boron/IM7 carbon/Epoxy (Hy-Bor®) composite specimens at Delsen Testing Laboratories[2] produced an average compression strength value of 413 ksi (50 MPa) using end-loaded, fully-supported flat test specimens per ASTM D695.

Since the early 1990's there has been a significant amount of compression test method development for high strength advanced polymer matrix composite materials. Most of this work has focused on the use of cross-plied laminates to derive equivalent 0^o lamina compression strength and modulus[3]. In a presentation review[4] of compression and shear properties performed on Hy-Bor material of similar construction (IM7 carbon fiber and Boron) as the Delsen/Bell Helicopter work, Dr. John W. Gillespie of the University of Delaware's Center for Composite Materials compared results obtained on 16-ply $[0]_{16}$ and $[0/90]_{4s}$ laminates using the IITRI test method. The [0]16 specimens delivered an average response of 321 ksi (2215 MPa) strength and 37 msi (255 GPa) modulus. The $[0/90]_{4s}$ specimen results averaged 230 ksi (1585 MPa) strength and 19 msi (130 GPa) modulus. Using his back out factor of 1.9, the equivalent compressive properties for the 0^o direction was reported to be 437 ksi (3015 MPa) and 36 msi (248 GPa). The use of the cross-plied laminate in compression testing of high strength polymer composites has now become widespread.

In similar work for Alliant Techsystems, Rocket Center, WV[5], Dr. Gillespie reported on the "Influence of Boron Fiber Count on Compressive and Shear Properties of Hy-Bor". His study was conducted using 16-ply $[0/90]_{4s}$ laminates of Boron/IM7/Epoxy Hy-Bor and the IITRI compression test method.

For this study five variations in the number of boron fibers per inch (fpi) in the Hy-Bor prepreg were produced and tested to determine the effects of percent boron fiber on compressive strength, modulus and % strain to failure. His results are presented in summary form in Table 1 and Figures 1 through 3. A representative stress-strain curve from each of the two selected fiber spacing's is shown in Figures 4 and 5. This study shows that beneficial improvements in compressive strength and modulus can be obtained at boron fiber additions between 100 fpi and 200 fpi. In part due to these results and in part due to manufacturing constraints, standard Hy-Bor® product offerings of 208 boron fpi and 100 boron fpi were established.

Table 1 – Data Table for

Boron Count (fpi)	Ave.Width (in.)	Ave. Thickness (in.)	Failure Load (lbs.)	Failure Stress (ksi)	Failure Strain (%)	Modulus (msi)	0° Lamina Strength (@ 1.9 BF)	0° Lamina Modulus (@ 1.9 BF)
50	0.496	0.065	3393	105.1	0.99	11.08	199.8	21.06
71	0.499	0.067	4621	137.8	1.08	12.96	261.9	24.62
100	0.499	0.071	6339	178.8	1.17	14.86	339.8	28.24
143	0.499	0.082	8200	199.8	1.25	15.94	379.7	30.28
200	0.4994	0.091	9562	209.4	1.10	18.53	397.9	35.21

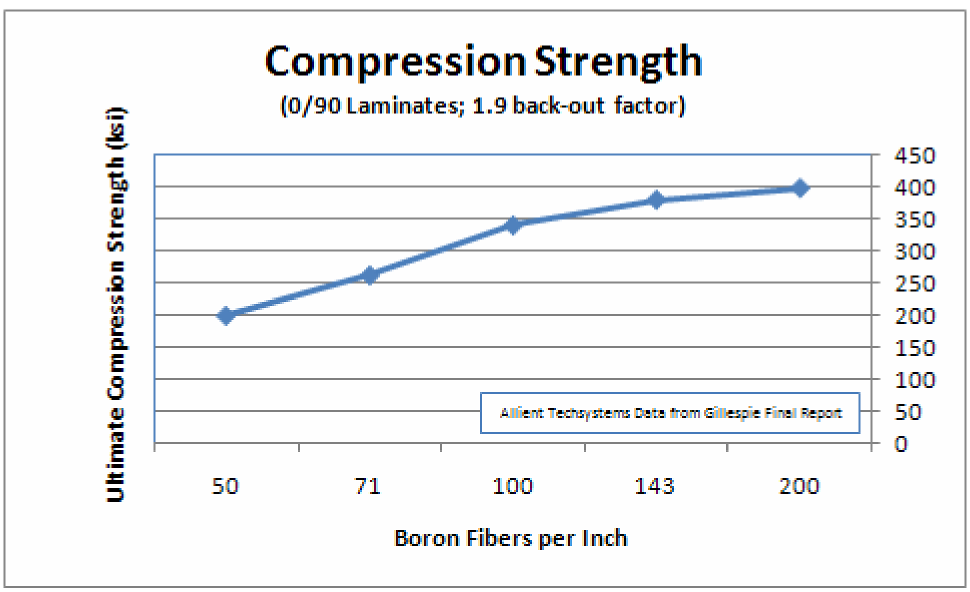

Figure 1 – Compressive Strength vs. Boron Fiber Count in Hy-Bor®

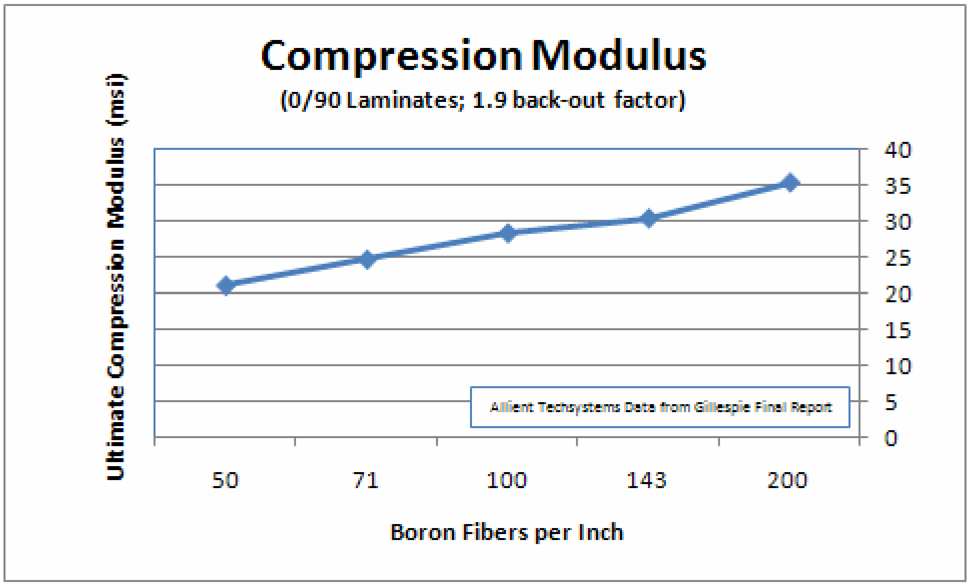

Figure 2 – Compressive Modulus vs. Boron Fiber Count in Hy-Bor®

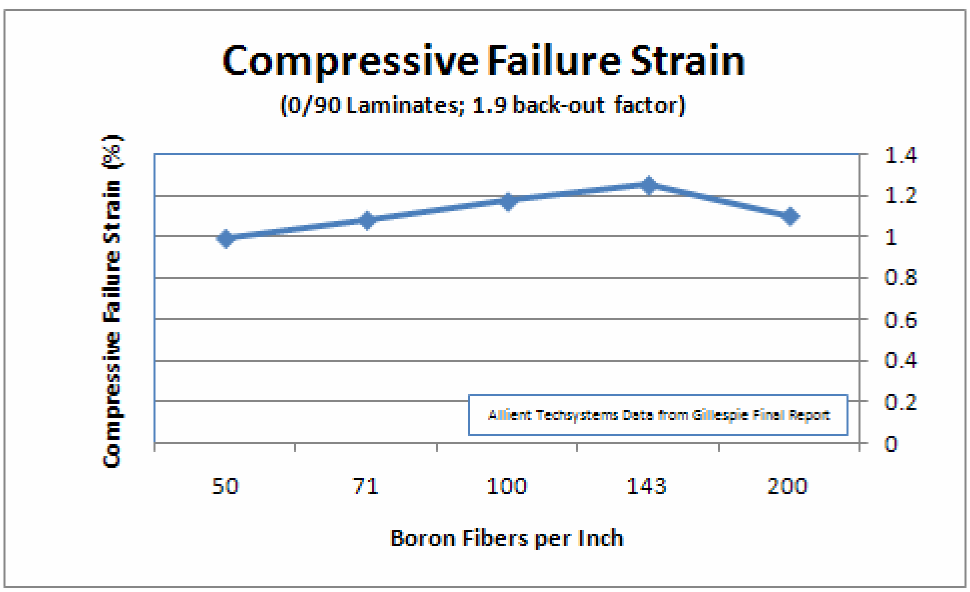

Figure 3 – Compressive Failure Strain vs. Boron Fiber Count in Hy-Bor®

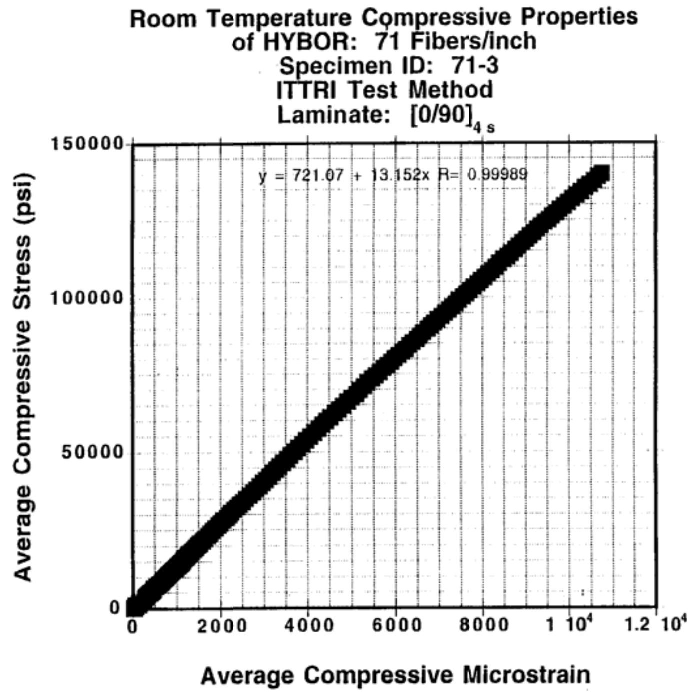

Figure 4 – Compressive Stress-Strain Plot for 71 fpi Configuration

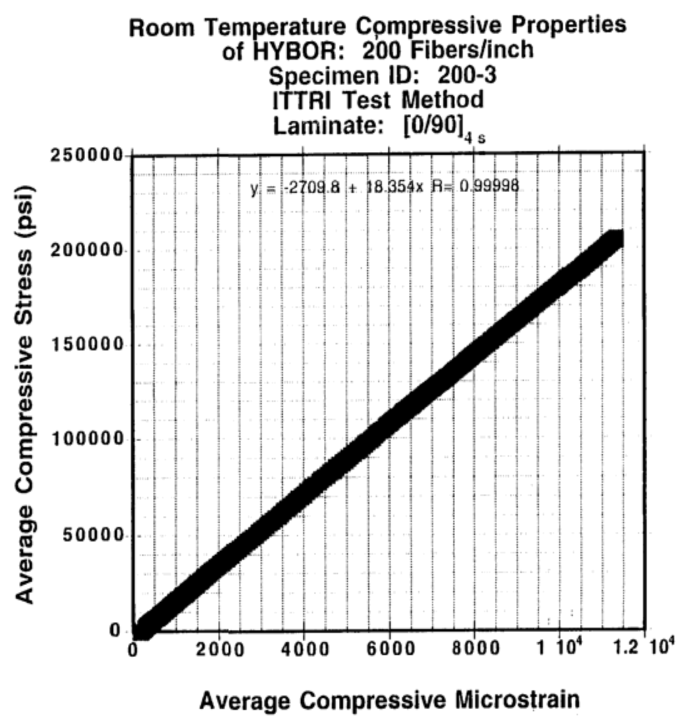

Figure 5 – Compressive Stress-Strain Plot for 200 fpi Configuration

The most recent work on compression test fixture development has addressed the potential for shear load introduction influences on resulting property values. The Wyoming Combined Loading Compression (CLC) test fixture[6] and associated ASTM D6641 Test Standard provides this combined loading and eliminated the need for tabbed specimens. This approach was used in a recent study[7] by Yeow Ng, Wichita State National Institute of Aircraft Research (NIAR) and Albert Kumnick, Specialty Materials, Inc. on the effect of [0/90] laminate stacking sequence on compressive properties (see the Yeow Ng, Al Kumnick SAMPE paper **Boron Compression Strength Analysis** under the **Products** tab). In this study, ply stacking sequences were varied to produce 0^o fiber volumes from 50% to 10%. The results obtained suggest that an optimal fiber volume for boron/Epoxy composite material is 20%. The results for the eight sequences evaluated are presented in Table 2. A plot of the results for compressive strength is shown in Figure 6.

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)

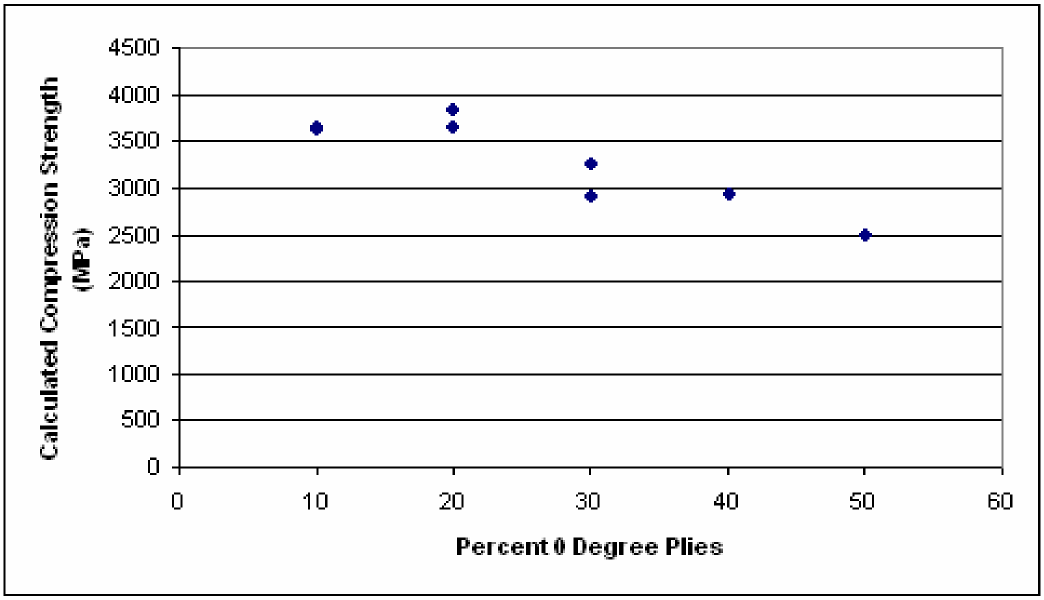

Figure 6 - Relationship between Calculated Compressive Strength and Percentage of 0º Plies

As a result of this study, a [0/90] compression test laminate configuration containing 20% 0^o plies and a stacking sequence of $[90/0/90/0/90/90/90/90/90/90]_s$ has become the preferred approach.

Although early Hy-Bor configurations were produced using a variety of carbon fiber grades and resins, two standards have evolved: Hy-Bor® 100 and Hy-Bor® 208. The configuration for these is a starting carbon fiber prepreg from Newport Adhesives and Composites containing 65 g/m^2 MR40 fiber and 65 g/m^2 301 resin into which a parallel array of either 100 fpi or 208 fpi boron is laminated. A small study was undertaken in late 2006 to compare our standard Hy-Bor 208 and Hy-Bor 100 compression strength, obtained by CLC fixture testing of the preferred laminate configuration, to the Gillespie results at comparable boron fiber count. The results for the base carbon prepreg and the two counts of Hy-Bor are presented in Table 3. A plot of the results for compressive strength is shown in Figure 7. Comparing Hy-Bor 100 results with the Gillespie study reveals the compression strengths (359.9 ksi vs. 339.8 ksi, respectively) to be reasonably the same. This is also true for the comparison between Hy-Bor 208 results and Gillespie's 200 count results (409.4 ksi vs. 397.9 ksi, respectively).

Table 3 – Data Table for Hy-Bor CLC Testing vs. 0^o Fiber Percent

V_f %	MR40/301	BF	0o Lamina	Hy-Bor 100	BF	0o Lamina	Hy-Bor 208	BF	0o Lamina
50	69.4	1.914	**132.8**	161.3	1.892	**305.2**			
40	59.8	2.342	**140.0**	141.9	2.303	**326.8**	158.4	2.245	**355.7**
33	53.3	2.752	**146.7**	124.2	2.693	**334.5**	155.7	2.606	**405.7**
20	38.3	4.236	**162.2**	88.4	4.071	**359.9**	106.7	3.837	**409.4**
10							64.5	5.944	**383.4**

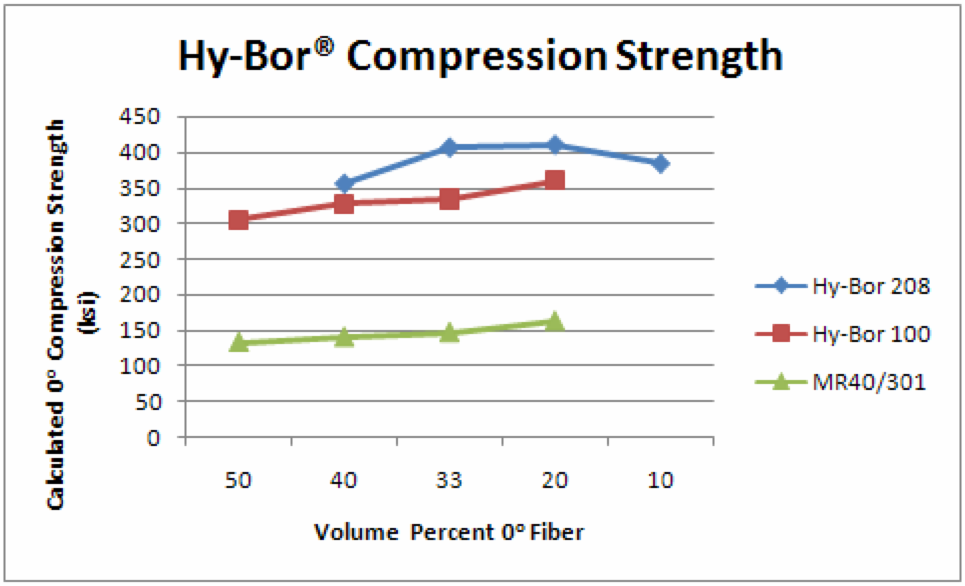

Figure 7 – CLC Test Results for Hy-Bor Configurations vs. 0° Ply Percentage

Prior to 2002 there was increasing composite manufacturing experience that showed a tendency for the boron fibers in Hy-Bor tape to lift from the surface when the tape was cut for lay-up. The lifting problem was particularly troublesome when cutting small pieces of prepreg. To solve this problem a 25 g/m^2 neat 301 resin film was added to the laminated boron fiber side of the prepreg tape. The downside of this fix was a lowering of the reinforcement volume fraction.

Newport Adhesives and Composites, the NCT-301 carbon prepreg producer, proposed two options to potentially improve the above situation. One was their ability to produce a thinner neat resin film (i.e. 18 g/m2 areal weight) and the other was a 110 g/m^2 prepreg configuration (70 g/m^2 MR40 graphite and 40 g/m2 NCT 301 resin) that could be produced with a resin rich surface on one side such that an additional neat film may not be needed.

Tensile tests were first performed to evaluate these alternate configurations. Test laminates were produced from the two optional Hy-Bor configurations described above standard Hy-Bor containing a 25 g/m2 resin film. All three configurations contained boron fiber content of 208 fpi (174 g/m^2). The test results are presented in Table 4.

The modulus improvement for the one-sided material in particular is very impressive. These improvements are consistent with higher reinforcing (boron plus graphite) volume fractions as calculated from average consolidated ply thickness, see Table 5. The one-sided material was subjected to careful examination on cutting prior to lay- the up and no significant boron fiber lifting was observed.

Table 4 - Tensile Strength and Modulus (average of 5 tests at RT)

Sample Type	Strength (ksi)	Modulus (msi)
Std. Hy-Bor Configuration	308	34.8
Thin film Hy-Bor	318	35.9
No film Hy-Bor	323	39.8

Table 5 - Consolidated Ply Thickness and Volume Reinforcement Fraction Calculation

SAMPLE TYPE	Avg. Ply Thickness Actual (in.)	V_f Actual
Std. Hy-Bor Configuration	0.0061	0.58
Thin film Hy-Bor	0.0060	0.60
No film Hy-Bor	0.0055	0.76

20-Ply test laminates were produced to the preferred configuration and tested by NIAR for compressive properties under CLC. A summary of the strength and modulus results for these configurations is presented in Table 6.

Table 6 – Compression Test Summary for Alternate Hy-Bor Constructions

			20% 0-deg Fiber Direction, 20-ply Composite			
			Composite Fcu (ksi)	@BF Fcu (ksi)	Composite Ec (msi)	@BF Ec (msi)
Hy-bor Tape Config.						
Hy-Bor 208	65g-MR40/65g resin	25g resin film	104.3	406.8	8.5	33.2
Hy-Bor 208	65g-MR40/65g resin	18g resin film	105.9	416.2	9.1	35.8
Hy-Bor 208	70g-MR40/40g resin	No film	123.3	508	10.3	42.4

References:

1. DoD/NASA Composite Handbook Design Guide, 1983.
2. Delsen Testing Laboratories, Mechanical Properties Testing on Boron/Carbon/Epoxy Material, Report No. T 32321 prepared for Bell Helicopter Textron, Fort Worth, TX, December, 1995.
3. L. J. Hart-Smith, “Backing Out Equivalent Unidirectional Lamina Strengths for Tests on Cross-Plied Laminates”, 37th International SAMPE Symposium, March 9-12, 1992, pp. 977-990.
4. J. W. Gillespie, “Testing and Analysis of XRod HyBor Materials”, presentation document, January 18, 1995.

5. University of Delaware Center for Composite Materials, J. W, Gillespie, Influence of Boron Fiber Count on Compressive and Shear Properties of HyBor, Final Report for Alliant Techsystems, Rocket Center, WV.
6. D .F. Adams, “Testing Cross-Ply vs. Unidirectional Composites”, High Performance Composites, March 2006.
7. Y. Ng and A. Kumnick, “Determination of Cross-Ply Laminate Stacking sequence for the Compression Strength Testing of a Unidirectional Boron Epoxy Material”, 2006 SAMPE Fall Technical Conference, Dallas, TX.