CHARACTERIZATION OF STRETCH BROKEN CARBON FIBER COMPOSITES – IM7 FIBER IN 8552 RESIN – STRETCHED AT PREPREG LEVEL

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ABSTRACT

Previous work has successfully demonstrated the equivalency of stretch broken carbon fiber (SBCF) composites for a wide range of mechanical properties compared to the corresponding material with continuous reinforcement.

Work continued with the investigation of composites made from stretch broken (SB) IM7/8552 prepregs stretched at the prepreg level in an attempt to simulate deformations that occur during forming of complex features like beads or raised regions shaped like Brodie helmets. The unidirectional stretching of SB IM7/8552 prepreg lay-ups was performed at elevated temperatures used in forming processes to allow material extension at reduced resin viscosity.

This paper presents mechanical properties of composites made from SB IM7/8552 prepreg lay-ups stretched at the prepreg level in comparison to material made from the SB prepreg in "as-made" condition. The intent is to determine if and how the forming process changes basic material properties. Select properties tested at ambient conditions include 0° tension, open hole tension and compression, in-plane and short beam shear, compression after impact, and bearing response. Results will be discussed with particular consideration of the prepreg contraction perpendicular to the stretch direction.

1. INTRODUCTION

Work conducted by Hexcel in the Navy-funded SBCF programs has been published in the 2005, 2007, 2009, and 2010 SAMPE conference proceedings. The continued development of Hexcel's stretch-break process led to production of stretch broken (SB) IM7 fiber with an average broken filament length as short as 5 cm (2.0 inch) and improved deformability [1]. Details of technology demonstrations of integrally bead-stiffened panels and 3D woven preforms can be found in [2, 3, 4].

With the development of SB (2.0") IM7 fiber in early 2008, testing of mechanical properties became a major effort within the past Navy-funded SBCF program, running from late December 2007 to the end of September 2010. The test matrices included a wide range of properties, which were selected based on material specifications of interest. Results on mechanical performance testing of “as-made” IM7/8552 with stretch broken and continuous reinforcement at room temperature dry (RTD), cold temperature dry (CTD), and elevated temperature wet (ETW) environments demonstrated equivalency of a wide range of strength and stiffness related properties of the SB IM7/8552 material form compared to the material form with continuous reinforcement [5].

Since forming of SBCF materials into complex shapes utilizes the extensibility of SBCF tows along the fiber axis, the characterization of composites made from pre-stretched SB IM7/8552 prepreg was the next-level investigation of interest for SBCF materials.

A consistent procedure was developed to stretch uncured SBCF prepreg stacks of the various lay-up sequences and dimensions as required by the composite test types, without significant misalignment of tow orientation, wrinkle generation, or further resin staging or degradation. These prestretched lay-ups were then cured into flat panels, from which mechanical test coupons were machined and subsequently tested to determine mechanical properties.

2. EXPERIMENTATION

2.1 Stretch Breaking of IM7 Carbon Fiber

A detailed description of Hexcel stretch break technology can be found in [1]. The Generation 2 Stretch Break Machine (SB2 Machine) was utilized to manufacture stretch broken IM7 tows, designated SB (2.0”) IM7-GP 12K.

2.2 UD Prepreg Manufacture

All SB IM7/8552 prepreg was manufactured on commercial prepreg lines at Hexcel’s SLC Matrix facility. The resin used was commercial film, also manufactured by Hexcel SLC Matrix utilizing standard operating procedures. Fiber areal weight (FAW) varied between 145 g/m^2 (for 0° lay-ups) and 160 g/m^2, at a nominal resin content of 35%.

2.3 Uncured Prepreg Stretching Procedure

Stretching of uncured prepreg stacks was a collaborative development effort with Pepin Associates at their Greenville, Maine facilities with the goal to have an uni-axial stretching method in place, aimed at preventing tow orientation, wrinkle generation, or further resin staging or degradation.

Common for all “generations” of stretching procedures was the bagging of the prepreg stack between thin silicone rubber sheets under vacuum.

Figure 1 illustrates the “Generation 1” stretching setup, placed into a tensile testing machine. The left picture shows the prepreg stack sandwiched between the 3.2 mm (1/8”) thick translucent silicone rubber sheets and connection to vacuum. Grips clamped the prepreg stack at top and bottom. Those shown in Figure 1 were 3.81 cm (1 ½ inch) wide and were later replaced by 6.35 cm (2 ½ inch) wide grips to provide reliable clamping.

Prepreg stacks were 30.48 cm (12.0 inch) wide, while the open space between the grips - corresponding to the gage length – was 33.02 cm (13.0 inch). Distance between the gridlines, drawn on the prepreg, was 2.54 cm (1.0 inch) to allow the determination of axial stretch and lateral contraction.

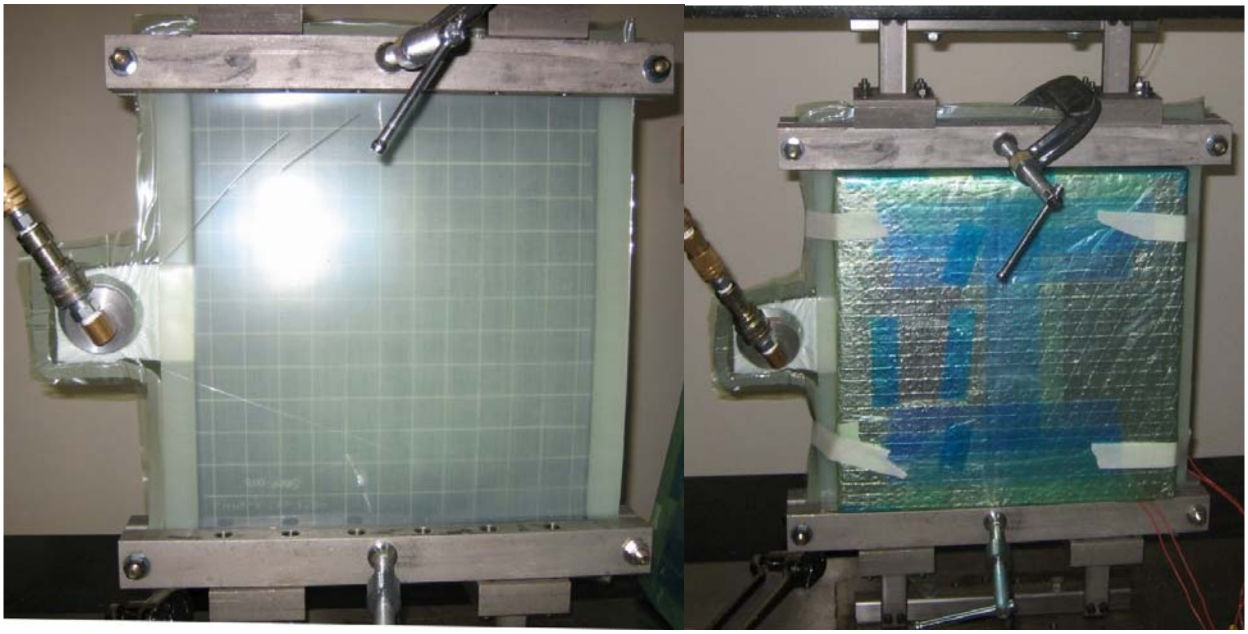


Figure 1: “Generation 1” Prepreg Stretching Setup
Left: Prepreg Stack Sandwiched between Silicone Rubber
Right: Heater Plates Attached (front and back)

The right picture in Figure 1 shows the setup with the heater plates attached. Targeted temperature, measured between heater plates and prepreg stack, was 110 °C, which was established as a standard for part forming trials of SBCF materials with 8552 resin.

The arrangement as shown in Figure 1 was utilized for the trial series SBPP-001 to -14 (0° lay-ups) and SBPP-025 to 027 (±45 lay-ups).

As described in Section 3.2, additional measures were deemed necessary to eliminate or at least significantly reduce the lateral contraction of the prepreg stack (and the silicone rubber sheets) during uniaxial stretching. After some unsuccessful attempts, the horizontal cross-bars were added to clamp the extended silicone rubber sheets at the left and right extremity to reduce the lateral contraction.

Figure 2 illustrates the “Generation 2” stretching setup, shown with one cross-bar across the panel vertical center. The cross-bar had an inner opening of 35.56 cm (14.0 inch), spanning the 30.48 cm (12.0 inch) wide prepreg stack perpendicular to the direction of stretch.

A few experiments were also conducted with two cross-bars, each offset by 5.08 cm (2.0 inch) from the perpendicular center line.

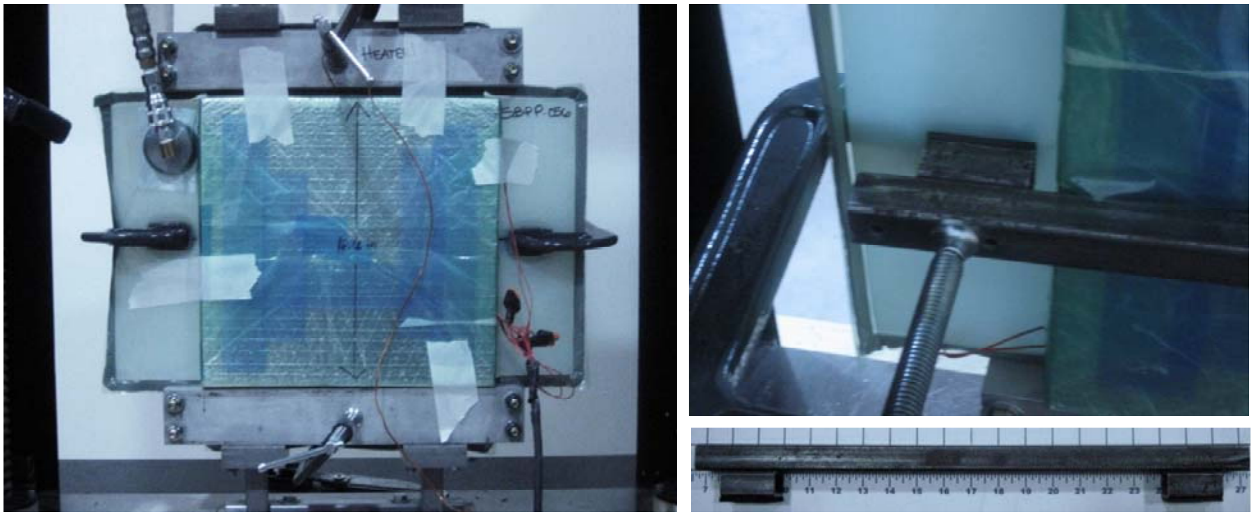


Figure 2: “Generation 2” Prepreg Stretching Setup– One Cross-Bar
Left: Front View of Assembly Ready for Stretching Trial
Right Top: Back View at Cross-Bar and C-Clamp
Right Bottom: Cross-Bar with 35.56 cm (14.0 inch) Inner Opening

2.4 Panel Fabrication

Panels were fabricated by Pepin Associates, Inc. from the SB IM7/8552 prepregs, using the standard 177 °C (350 °F) HexPly® 8552 autoclave cure cycle. “As-made” SB IM7/8552 served as controls to those pre-stretched at the prepreg level. Panels were designated by “SBPP” (for Stretch-Broken Pepin-made Panel), follow by a 3-digit serial number.

Note: All panels designated UDC08-001 and -002, and SBT08-003 to 007 in the charts of section 3 were fabricated previously and test results from these panels were published in [5].

Cured panel dimensions were typically 30.48 cm (12.0 inch) or 33.02 cm (13.0 inch) by 25.40 cm (10.0 inch), with the longer edge parallel to the stretch direction.

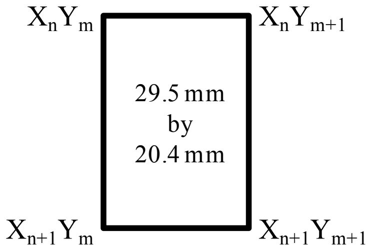
NDI testing of the panels by C-scan was performed by the National Institute for Aviation Research (NIAR) at Wichita State University (WSU).

2.5 Grid Line Evaluation

Grid lines were manually drawn on the surface of the prepreg stack using a marker, type Pilot Silver Marker – Extra Fine Point, to serve as a reference for the undeformed lay-up coordinates. These lines were drawn at a spacing of 25.4 mm (1.0 inch), with an estimated accuracy of ± 0.2 mm.

As stretching of the prepreg stack occurred, this grid marking deformed with the material. After cure of the prepreg, a copy of the stretched panel surface was made by optical scanning to generate a digital image of the deformed grid line pattern. To make the grid lines more apparent the copy settings used reversed the black and white color intensity to make the pattern as black lines on a white background.

Axial stretch and lateral contraction were determined by measuring coordinates of the grid line crossing points. The axial stretch ε_x (in %) was calculated using equation [1], the lateral contraction ε_y (in %) using equation [2].



$$\varepsilon_x = ((X_{n+1}Y_m - X_nY_m) + (X_{n+1}Y_{m+1} - X_nY_{m+1}))/(2\cdot 25.4) \quad [1]$$

$$\varepsilon_y = ((X_nY_{m+1} - X_nY_m) + (X_{n+1}Y_{m+1} - X_{n+1}Y_m))/(2\cdot 25.4) \quad [2]$$

The rectangle, shown above, reflects the change of the 25.4 mm (1.0 inch) square in the center of SBPP-025 after an overall stretch of 10% (see also Figure 6 in Section 3.1.2.).

2.6 Test Specimen Fabrication, Testing and Data Reduction

These tasks were performed by either NIAR/WSU or the Hexcel SLC Matrix Test Lab. Testing methods (standards) were the same as listed in Table 4 of [5].

All testing in this paper was performed in a room temperature dry (RTD) environment.

Strengths and moduli were calculated using the actual cross-section of the test coupons (for fiber dominated properties), then normalized to 60% fiber volume. All panels, for which mechanical testing data is reported here, were tested for fiber volume and void volume by the acid digestion method.

3. RESULTS

Results are presented in chronological order, starting with stretch trials utilizing the Generation 1 setup, following by the illustration of the effect of lateral contraction, and concluding with the mechanical performance data obtained utilizing the Generation 2 setup, which includes one or two cross-bars.

3.1 Stretch Trials with Generation 1 Setup (without Cross-Bar)

After preliminary stretching trials with encouraging outcomes, a first set of stretching trials was performed on 0° prepreg lay-ups for 0° tension and short beam shear testing. ±45 lay-ups for in-plane shear testing were stretched in a second series. The overall stretch was set at 10%.

3.1.1 0° Panels (SBPP-001 to -014 Series)

The Table 1 below gives an overview of the 0° panels, of both stretched as uncured prepreg and the corresponding control panels:

Table 1: 0° Panels (SBPP-001 to -014 Series)

Panel ID	SB Tape ID (145/35)	Ply Sequence	Overall Stretch [%]	Fiber Vol. [%]	Void Vol. [%]
SBPP-001	SBT08-003	$[0°]_8$	10.0	56.15	0.15
SBPP-007			Control	56.05	0.23
SBPP-008	SBT08-004		10.0	56.62	0.70
SBPP-014			Control	57.28	0.30
SBPP-006	SBT08-003	$[0°]_{6x3}$	10.0	56.69	-/-
SBPP-013	SBT08-004			57.08	0.16

The 8-ply panels (SBPP-001 and -008) were stretched as 8-ply prepreg stacks, while the 18-ply panels - shown as $[0°]_{6x3}$ - were stretched as 6-ply prepreg stacks. Three of these stretched 6-ply stacks were then cured together to fabricate 18-ply panels.

Most of the C-scans looked clear, although it should be noted that the controls looked “cleaner”. The void volume test data of SBPP-006, shown in Table 1 as “-/-“, was negative.

3.1.1.1 0° Panels - Tensile Test Results

In the left part of Figure 3, a (B&W reverse) copy of SBPP-001 after an overall stretch of 10% is shown. The direction of the uni-axial stretch is indicated by the arrow in the panel center. Before stretch, the grid lines were 2.54 cm (1.0 inch) square. The effect of the 10% overall stretch and of the accompanying lateral contraction can be easily recognized by the change in shape of the originally square grid.

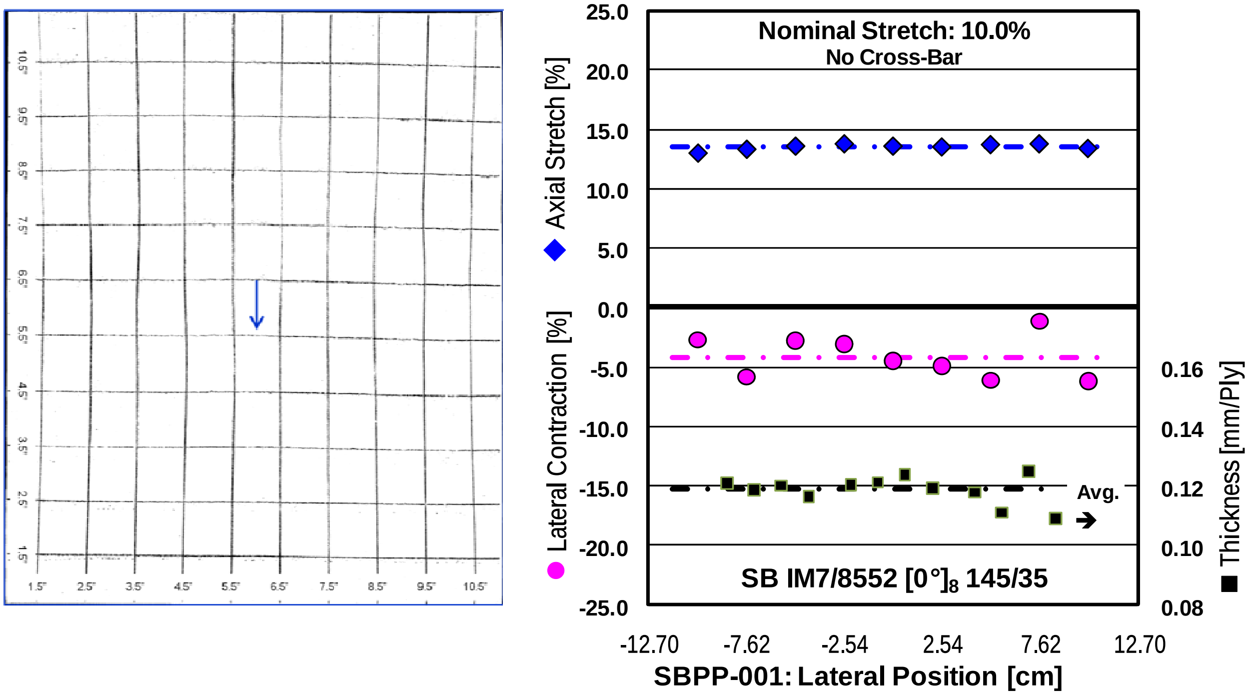


Figure 3: 0° Panel SBPP-001 Stretched at Prepreg Level by Overall 10%
Grid Lines (Left) and Evaluation Results (Right)

In the right part of Figure 3, the axial stretch and the lateral contraction as well as the thickness of the tensile specimens are charted over the transverse position of the cured panel.

The effective axial stretch (ε_x) in the center of the panel is reasonably uniform across the panel and averages 13.5%. The stretch in the center has to be higher than the overall stretch of 10.0%, because filaments are clamped by the top and bottom grips and have their first break inside the prepreg stack according to their break length and its distribution. Compared to the 13.5% stretch in the panel center, the average lateral contraction (ε_y) of 4.13% is within expectations, considering the Poisson's ratio of 0.50 for silicone rubber and estimated 0.36 for UD CF prepreg.

The panel thickness across the panel is a kind of "mirror" of the lateral contraction at the same or similar position. However, the panel, or tensile specimen thickness per ply is much smaller than that calculated from axial stretch, lateral contraction, and thickness of the (unstretched) control panel, made from the same prepreg batch, SBT08-003. Thinning of the stretched prepreg can be derived from the conservation of mass; i.e. the volume of the original 25.4mm x 25.4mm grid element must be preserved after stretching has occurred. This is expressed by:

$$a_u \cdot b_u \cdot t_u = a_d \cdot b_d \cdot t_d, \text{ therefore} \qquad [3]$$

$$t_u = (1+\varepsilon_x)\cdot(1+\varepsilon_y)\cdot t_d, \text{ or} \qquad [4]$$

$$t_d = \frac{t_u}{(1+\varepsilon_x)\cdot(1+\varepsilon_y)}, \text{ or for small strains } \varepsilon_x, \varepsilon_y << 1\text{: } t_d \cong \frac{t_u}{(1+\varepsilon_x+\varepsilon_y)} \qquad [5]$$

Where t_u, t_d = thickness, a_u, a_d = width, and b_u, b_d = height (undeformed, deformed), and

ε_x, ε_y = forming strain (axial, lateral)

In Figure 4, the 0° tensile strength of the individual test coupons of SBPP-001 and -008 (Stretched at Prepreg Level) and of the "As-Made" controls (SBPP-007 and SBPP-014) is shown over their position on the cured panel. Test coupons from the center of the panel, where misalignment was minimal to zero, show tensile strength values very comparable to those of the control panels. The tensile strength appears reduced in the test coupons closer to the edges of the panels, where slight ply angular misalignment results from the lateral contraction effects.

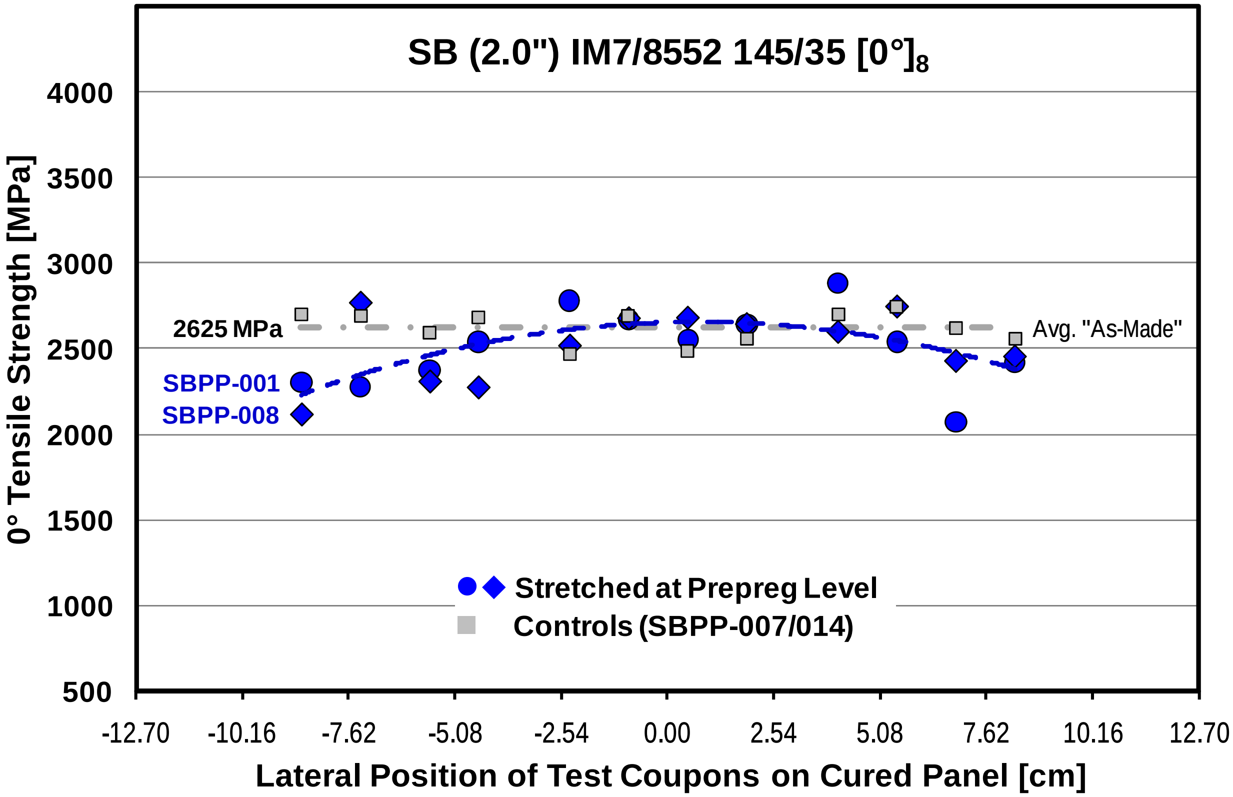


Figure 4: 0° Tensile Strength of SB (2.0") IM7/8552 Panels "Stretched at Prepreg Level" in Comparison to Control Panels Made from SB Prepreg "As Made"

Tensile modulus did not show this distinctive behavior. The two panels "Stretched at Prepreg Level" yielded 172.1 GPa (25.0 Msi) versus 164.6 GPa (23.9 Msi) of the unstretched controls.

3.1.1.2 0° Panels - Short Beam Shear (SBS) Test Results

The SBS strength results of the "Stretched at Prepreg Level" panels SBPP-006 and -013 are shown in Figure 5 in comparison to SBS strength data previously published in [5]. Eight (8) test coupons each were taken systematically distributed from the inner 21.6 cm by 19.1 cm area of the SBS panels of 30.48 cm by 25.4 cm. The 11.5% stretch value was determined from the grid lines of the entire area, from which the test coupons were taken. The SBS strengths were reasonably uniform across the test specimen locations on the panel.

The SBS strength of the two SBPP "Stretched at Prepreg Level" panels averaged 130 MPa (18.8 ksi), quite comparable to the SBT "As Made" controls, in particular when considering that this type of SBPP panel was fabricated from three individually stretched 6-ply prepreg stacks.

The difference between the SBS strength of IM7/8552 made from prepreg with continuous reinforcement (UDC) and that of IM7/8552 made from Stretch Broken prepreg "As Made" was discussedin [5].

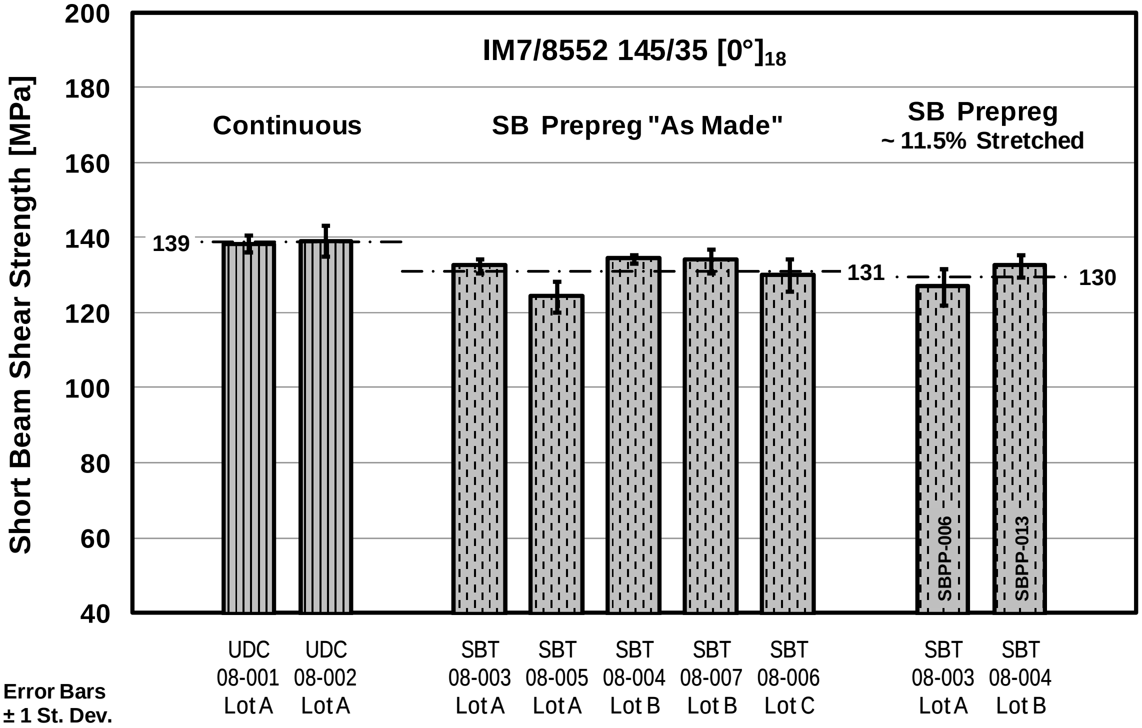


Figure 5: Short Beam Shear Strengths of IM7/8552 Made from Prepreg with Continuous Reinforcement (UDC), from Stretch Broken Prepreg (SBT) "As Made" and "Stretched at Prepreg Level"

3.1.2 ±45° Panels for In-Plane Shear (IPS) Testing (SBPP-025 to -027 Series)

In a next series of stretching trials, two 8-ply ±45° prepreg stacks, designated SBPP-025 and -026, were stretched by 10% overall.. The panel designated SBPP-027 served as an unstretched, "As Made" control.

In the left part of Figure 6, a (B&W reverse) copy of SBPP-025 after an overall stretch of 10% is shown. The direction of the uni-axial stretch is indicated by the arrow in the panel center. Before stretch, the grid lines were 2.54 cm (1.0 inch) square. The effect of the 10% overall stretch and of the accompanying lateral contraction is recognized by the change in shape of the originally square grid.

In the right part of Figure 6, the axial stretch and the lateral contraction as well as the thickness of the IPS test coupons are charted over the lateral position of the cured panel SBPP-025. SBPP-026 showed very similar results.

The effective stretch reached a maximum of approximately 17% in the (transverse) center of SBPP-025, declining to ~ 10% at the left and right edges. The lateral contraction shows a similar behavior, but much more extreme with a maximum of 20% in the center. The thickness, measured on the IPS test coupons, appears to have a (slight) maximum in the (transverse) center of SBPP-025.

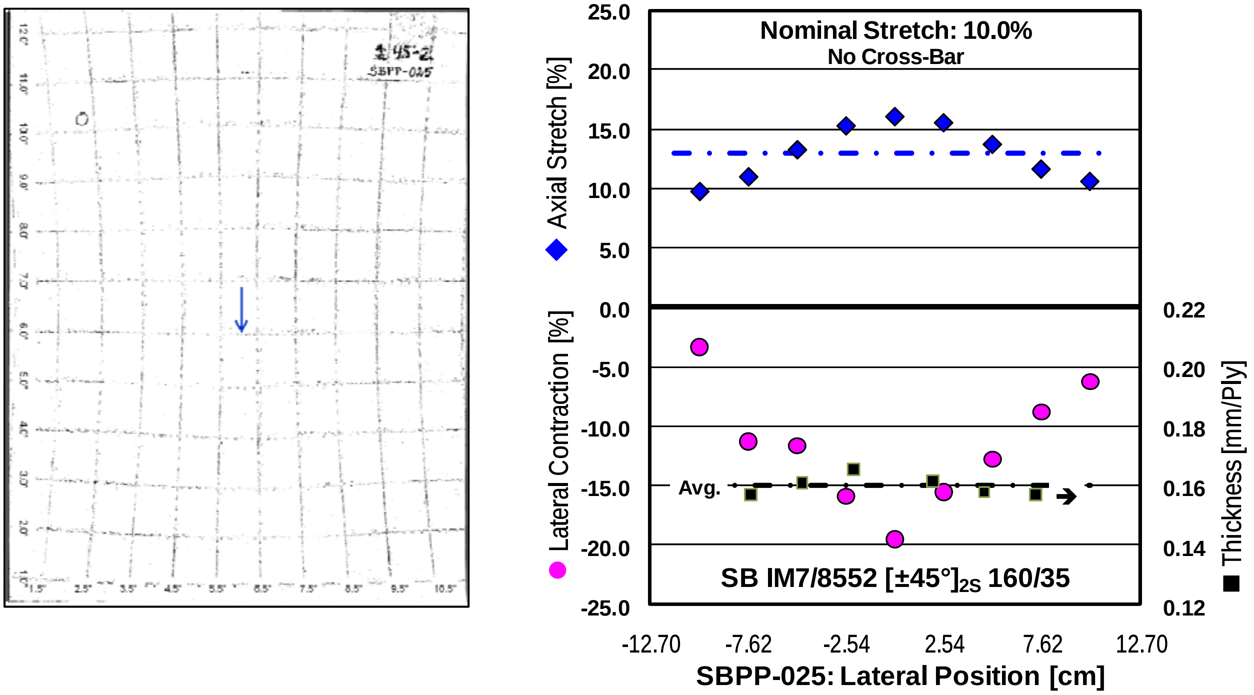


Figure 6: ±45° Panel SBPP-025 Stretched at Prepreg Level by Overall 10%
Grid Lines (Left) and Evaluation Results (Right)

Figure 7 illustrates the change of the ±45° lay-up angle of panel SBPP-025 after stretch by an overall of 10%. The lay-up angles were calculated based on the deformation of the grid lines shown in the left part of Figure 6 above. The ■ markers on the x-axis indicate the position of the (six) test coupons on the panel.

The two sketch inserts in the chart (left and right) show the test direction relative to the stretch direction. For “Tested Parallel to Stretch Direction”, the angles are shown for the lateral center of the panel, while for “Tested Perpendicular to Stretch Direction” they are shown for the vertical center of the panel.

In the center of the panel, the original ±45° lay-up angle is changed to approximately ±35° in the X direction (blue lines), while in the Y direction (green lines) the angle is increased to approximately ±55°.

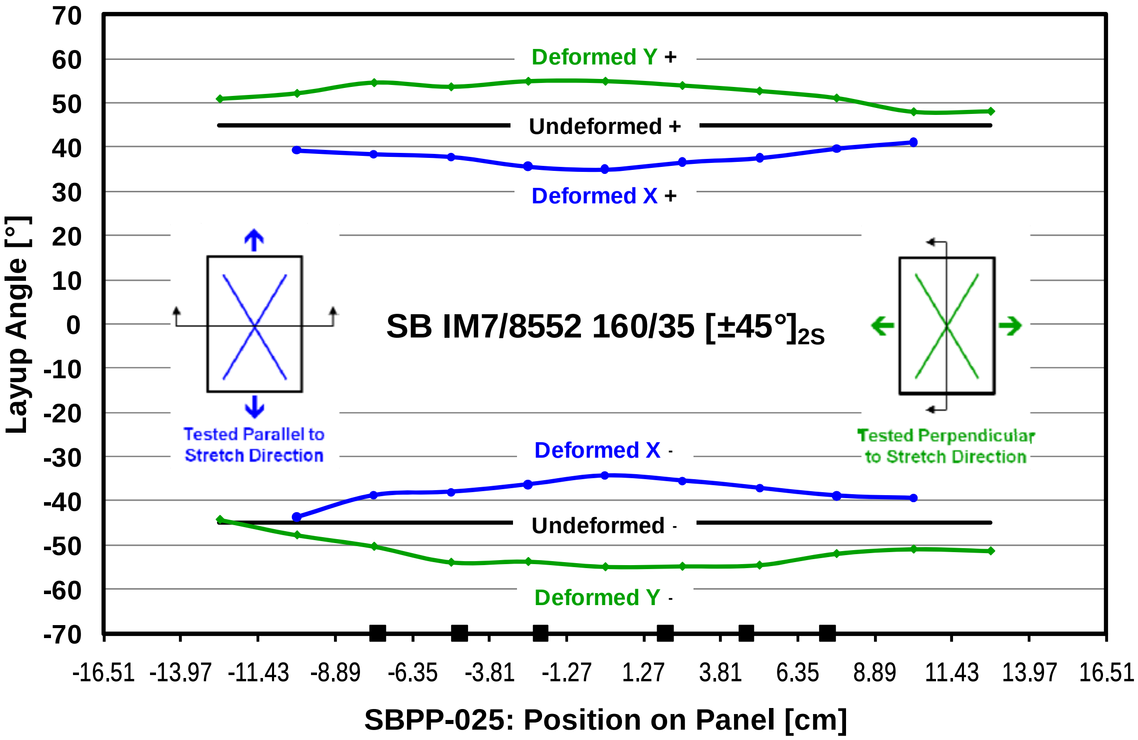


Figure 7: Lay-up Angle of ±45° Panel SBPP-025 after Stretch at Prepreg Level by Overall 10% and Position of Test Coupons (■ Markers on X-Axis)

The IPS strength of the SBPP-025 to -027 series is shown in Figure 8. The calculation of in-plane shear properties per ASTM D 3518 was modified for the panels "Stretched at Prepreg Level" (SBPP-025 and -026) as described below.

ASTM D 3518 describes the calculation of in-plane shear strength and modulus of 0° unidirectional materials from a tension test of a ±45° lay-up. The data reduction method is premised on the resolved stresses in the +45° and -45° plies. The applied coupon stress, when rotated into the ply axes, has a magnitude equal to 0.50 times the applied coupon stress. Using classical laminated plate theory (CLPT), the stresses in the unidirectional +45° and -45° plies – 0° or axial stress, 90° or transverse stress, and in-plane stress – can be calculated.

In the case of a +45 and -45 ply, the applied stresses in the fiber and transverse directions are so small, relative to the lamina strength in these directions, that they can effectively be ignored because they do not contribute significantly to laminate failure. Consequently, failure is driven only by the in-plane shear stress in the ply, which happens to be 0.50 times the applied coupon stress for a ±45° lay-up. The data reduction procedure of ASTM D 3518 assumes this condition and was used to calculate the reported in-plane shear strength and modulus for the "As Made" panel SBPP-027.

In a panel "Stretched at Prepreg Level", the laminate angles no longer remain at ±45° due to the combined effects of axial stretch and lateral contraction. In fact, the as-stretched lay-up angles vary across the panel width with the variation of axial and lateral strain, as illustrated in Figure 7.

Where in-plane shear was tested parallel to the stretch direction, the lay-up angles decreased as the fibers realigned in the direction of the load during stretching. Based on calculations from grid line measurements, the lay-up angles across the mid-plane panel ranged from ±35° to approximately ±40° for the outer test coupons.

Conversely, where in-plane shear was tested perpendicular to the stretch direction, the lay-up angles increased as the fibers realigned in the stretch direction (perpendicular to the test direction). In this case lay-up angles across the center panel were typically from ±55° for the test coupons.

For these "stretch" cases, the in-plane shear strength and modulus were calculated from the test data using the measured lay-up angles and CLPT. The same assumption used in ASTM D 3518, that shear stress is the predominant failure mode, is used here, and the maximum ply stress failure criteria was used to calculate the shear strength. CLPT analysis was also used to calculate in-plane shear modulus.

The in-plane shear strength and modulus of the ±45° panels SBPP-025 to -027 is shown in Figure 8 and 9, respectively.

SBPP-027: This "As Made" control panel yielded an IPS strength of 93.6 MPa (13.6 ksi), and the IPS modulus averaged 5.07 GPa (0.736 Msi), both very constant across the panel.

SBPP-025: For this panel, both stretch and test load direction were in the same direction. Compared to the "As Made" control, the in-plane shear strength is higher, even when calculated using the modified ASTM D 3518 procedure. Note that although the strains and ply angles vary significantly across the panel width, the CLPT data reduction procedure shows much less width variation than the as-stretched shear properties calculated using the conventional ASTM D 3518 procedure.

SBPP-026: For this panel, the stretch and test load direction were perpendicular. Compared to the "As Made" control, the average in-plane shear strength is lower, by 28% when calculated using ASTM D 3518, or 20% when using the CLPT data reduction procedure.

The in-plane shear modulus of the SBPP-025 to -027 series is shown in Figure 9. Using the CLPT data reduction procedure, there is almost no variation of the SBPP-025 modulus across the panel width and the moduli for the three types of panels were very similar.

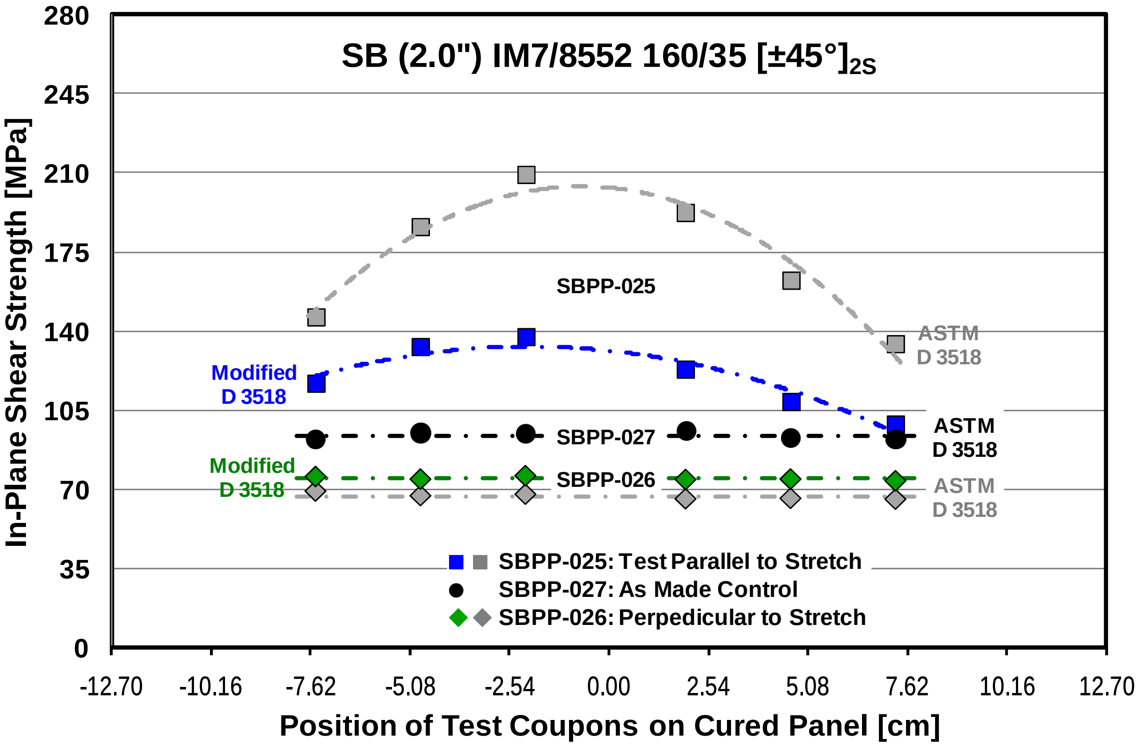


Figure 8: In-Plane Shear Strength of 8-Ply ±45 Panels SBPP-025 to 027

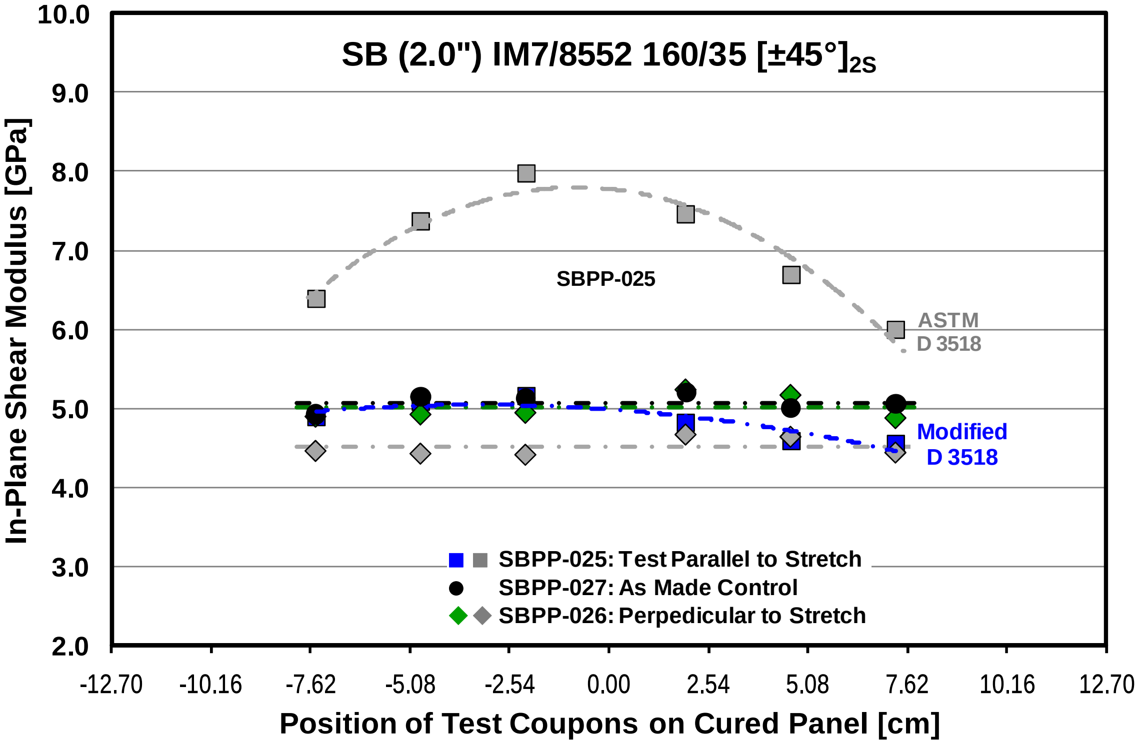


Figure 9. In-Plane Shear Modulus of 8-Ply ±45 Panels SBPP-025 to -027

3.2 Initial Attempts to Stretch Quasi-Isotropic (QI) Prepreg Stacks

After the encouraging results obtained on 0° lay-ups and interesting behavior of in-plane shear strength and modulus, focus shifted to stretching of QI prepreg lay-ups. When uni-axial stretch is applied in the 0° ply direction, there is no doubt that the 90° plies will create wrinkles if lateral contraction cannot be prevented.

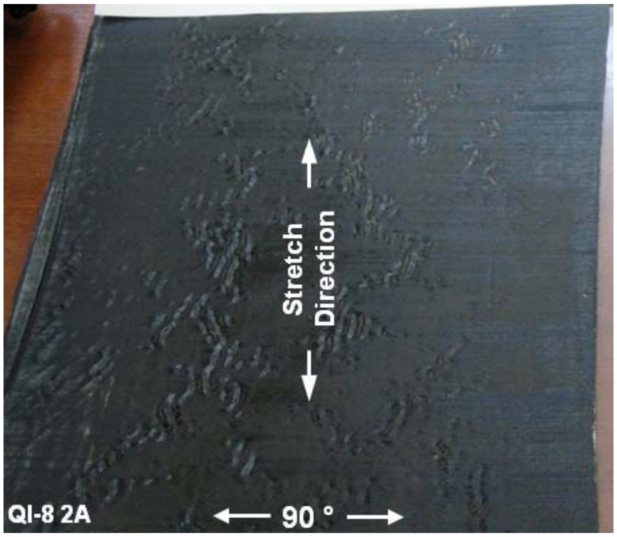


Figure 10: Photographic Picture of a QI 8-Ply Prepreg Stack after 10% Overall Stretch

Initial stretching trials on QI 8-ply prepreg stacks made it clear that lateral contraction, induced by the Poisson effect, causes wrinkling of the 90° plies.

The photograph in Figure 10 illustrates the slightly concave shape of the (vertical) edges as a result of the Poisson effect and wrinkle formation of the 90° plies.

Several approaches were tested to prevent wrinkle formation. These tests found that visible wrinkle formation of the 90° plies of QI prepreg stacks could be prevented by clamping the perpendicularly extended silicone rubber sheets, as described in Section 2.3.

The results shown in section 3.3 were obtained on cured panels, of which prepreg stacks were stretched utilizing one, or in a few cases, two horizontal cross-bars.

3.3 Stretch Trials with Generation 2 Setup Utilizing Horizontal Cross-Bar(s)

3.3.1 ±45° Panels for In-Plane Shear (IPS) Testing (SBPP-031 to -034 / -038 to -039)

Panels SBPP-031 and -033 were stretched utilizing one (1) cross-bar, SBPP-032 and -034 utilizing two (2) cross-bars, all by an overall 10%. SBPP-038 and -039 served as unstretched, “As Made” controls.

The effect of the number of cross-bars – none, one, and two – on the lateral contraction is shown in Figure 11. The “no cross-bar“ panel was SBPP-025, of which grid line dislocation after stretch was shown in Figure 6. SBPP-031 represents the data for one cross-bar, and SBPP-032 for two crossbars. SBPP-025 and -026 had no cross bar (⓿), -031 and -033 utilized one cross-bar (❶), and -032 and -034 utilized two cross-bars (❷).

The application of one cross-bar reduced the maximum lateral contraction in the panel center to ~ 12%, and of two cross-bars to ~ 7% compared with almost 20% with no cross-bar. Although there is no doubt that traverse clamping helps suppress the Poisson effect, the IPS strength behavior of SBPP-031 to 034, when plotted across the panel, was very similar to the data shown in Figure 8 for SBPP-025 and -026, which were stretched without a cross-bar. The same statement applies to the IPS modulus.

Figure 12 below shows the IPS strength of the SBPP-025 to -027 series together with IPS strengths of the UDC08 and SBT08 panels published in [5]. These values are comparable with those of SBPP-027, -038, and -039, which served as “As Made” controls in this investigation.

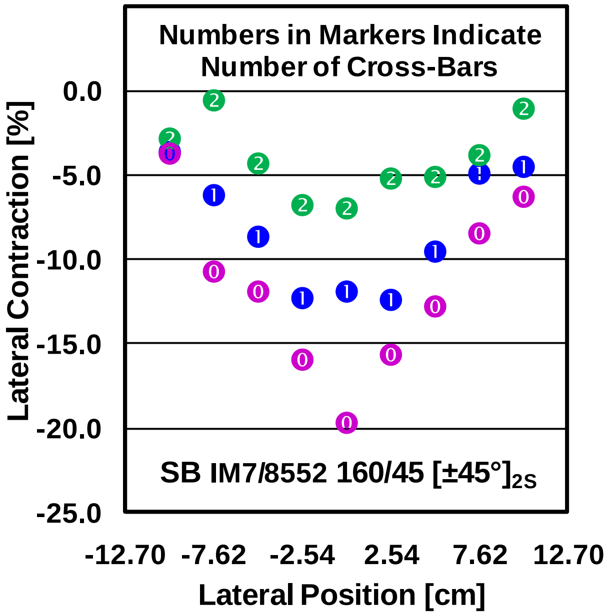


Figure 11: Lateral Contraction of ±45° SB IM7/8552 Panels Stretched by overall 10%

The data points in the right section – arrows symbolizing the direction of stretch at prepreg level and that of the test load – represent the IPS strengths of the SBPP panels stretched at prepreg level by overall 10%.

As stated above, the horizontal cross-bars helped suppress the lateral contraction. However, the IPS strength appears to be decisively controlled by the change of the ply angle. Applying an overall stretch of 10%, the ply angle of originally ±45° will change to approximately ±35° (in stretch direction) and ±55° (perpendicular to stretch direction), with the maximum change occurring in the panel center.

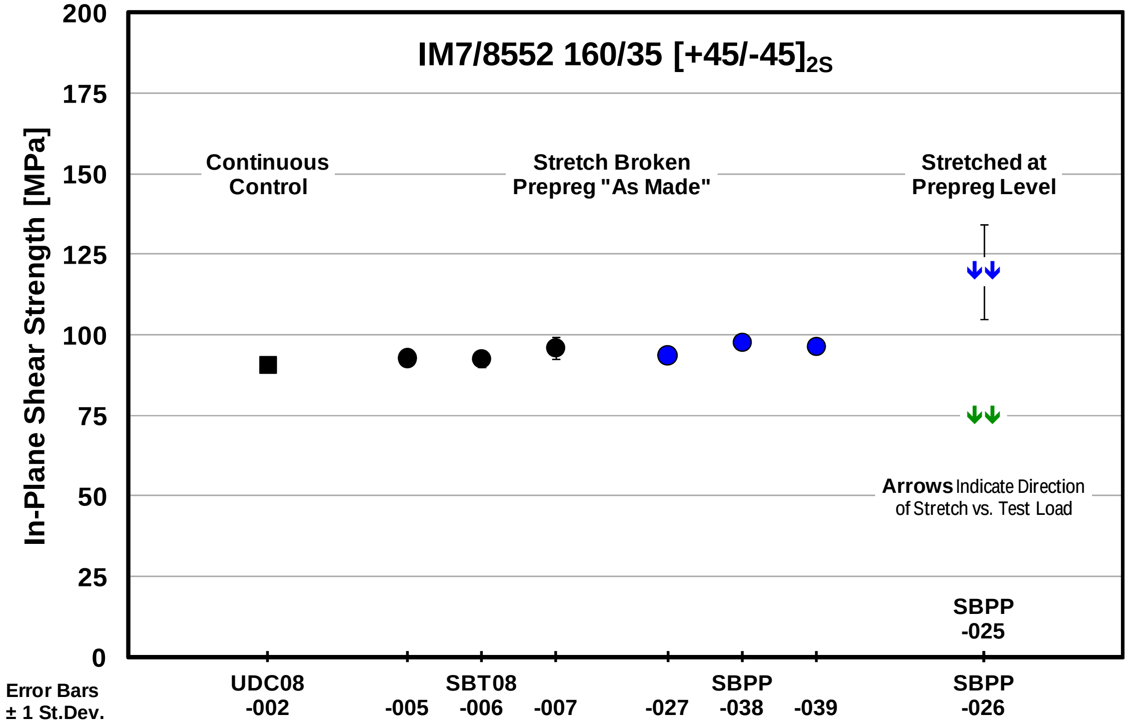


Figure 12: Comparison of In-Plane Shear Strength of Continuous IM7/8552, Stretch Broken “As Made, and Stretched at Prepreg Level (by overall 10%)

3.3.2 *Quasi-Isotropic 16-Ply Panels Bearing Response (A) Testing*

The results on Bearing Response (Procedure A) of SB IM7/8552 are shown in Table 2 below. Panels designated SBT08-007 and SBPP-042 represent SB Prepreg "As Made", and SBPP-043 and -044 "Stretched at Prepreg Level" by 11.2% and 3.9%, respectively. The 2%-Offset Strength of SBPP-042 is not available due to the extensometer being removed too early. Test load was applied in the same direction as that of stretch at prepreg level.

Table 2: Bearing Response (Procedure A) Strength of SB IM7/8552 160/35

Panel Designation		**SB Prepreg "As Made"**		**Stretched at Prepreg Level**	
		SBT08-007	**SBPP-042**	**SBPP-043**	**SBPP-044**
Stretch (at center)	[%]	N/A	N/A	11.2	3.9
Peak Strength	[MPa]	1001	1020	1006	1046
Stand. Dev.	[MPa]	39.1	41.9	49.1	24.4
2%-Offset Strength	[MPa]	957	N/A	931	950
Stand. Dev.	[MPa]	38.1		15.9	44.1

Apparently, there is no difference in bearing response, peak, and 2%-offset strength between the two materials, SB Prepreg "As Made" and "Stretched at Prepreg Level".

3.3.3 *Quasi-Isotropic 16-Ply Panels for Open Hole Tension and Compression Testing*

The results on Open Hole Tension and Compression testing are shown in Figure 13 (OHT) and Figure 14 (OHC). Test load of the panels "Stretched at Prepreg Level" was parallel to the stretch direction.

In Figure 13, the OHT strength of the three panels "Stretched at Prepreg Level" is compared to that of Continuous IM7/8552 controls (UDC08-001 and -002) and SB IM7/8552 panels made from Prepreg "As Made". One horizontal cross-bar was used to clamp SBPP-021, and two were used to clamp SBPP-022. In the case of SBPP-060, one cross-bar was used, but, in an attempt to make the clamping more effective, the 90° plies were extended to the clamps of the cross-bar. Independent of the horizontal clamping method, formation of visible wrinkles was suppressed.

Analogous to the ±45° IPS test data trends, the OHT strength of the "Stretched at Prepreg Level" panels is higher by about 20% than that of the controls, resulting from the change of ply angle from ±45° to approximately ±40°. The OHT modulus of the "Stretched at Prepreg Level" panels shows similar behavior.

Several QI 16-ply panels were made at various stretch ratios, using one horizontal cross-bar, ranging from approximately 4% to 16% in the center of the test coupons, which were tested for Open Hole Compression (OHC).

In Figure 14, the OHC strength and modulus are plotted versus the stretch ratio of the individual test coupons. The numbers in the markers are the last two digits of the panel designations. The "49" at 0% stretch represents SBPP-049, the unstretched "As Made" control.

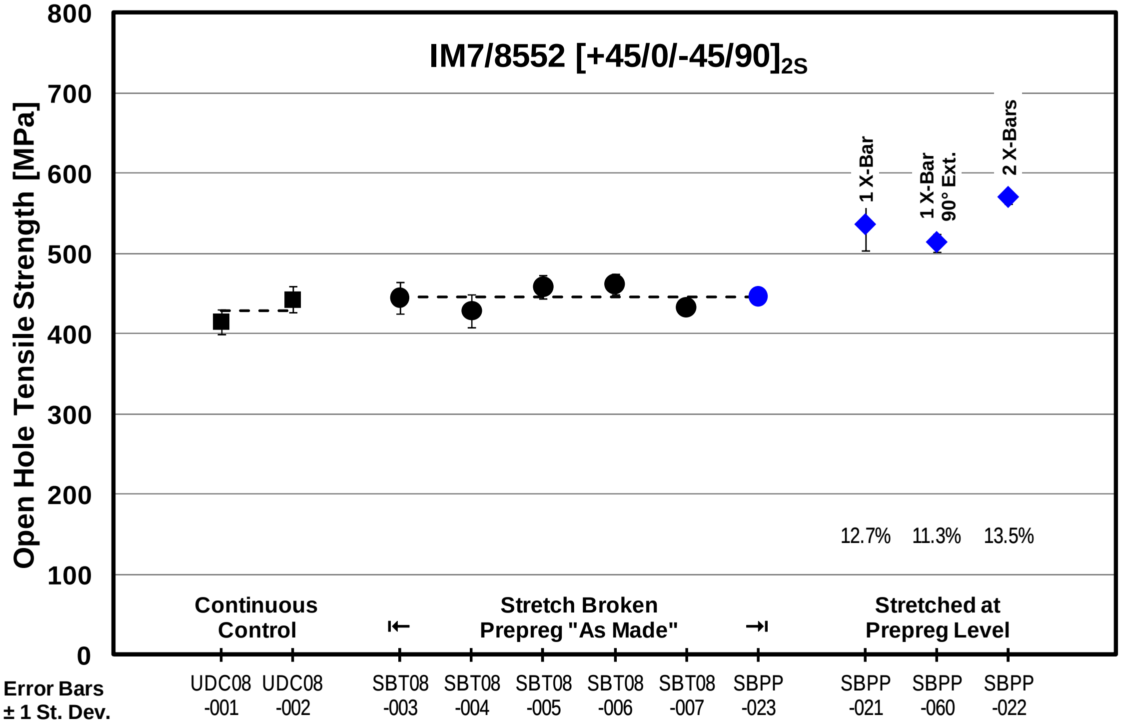


Figure 13: Comparison of Open-Hole Tension Strength of Continuous IM7/8552, Stretch Broken "As Made, and Stretched at Prepreg Level (by overall 10%)

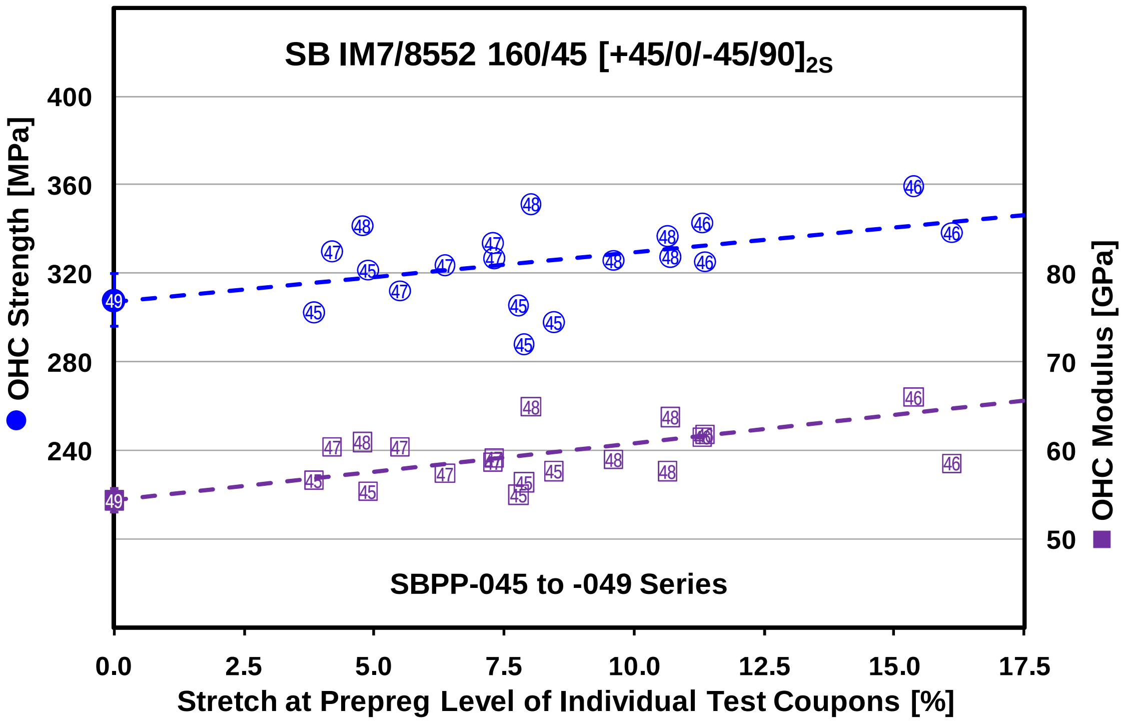


Figure 14: Open Hole Compression Strength and Modulus of Individual Test Coupons versus the Stretch Ratio at Prepreg Level

Although there is some scatter, both OHC strength and modulus increased with increased stretch ratio at the prepreg level, consistent with the behavior of the OH tension properties.

OH tension and compression tests on the test load perpendicular to the stretch direction were not conducted due to limitations in cured panel width.

3.3.4 Quasi-Isotropic 32-Ply Panels for Compression after Impact (CAI) Testing

In Figure 15, the Compression after Impact strength is shown for Continuous IM7/8552 controls (UDC-08-001 and -002), Stretch Broken Prepreg "As Made" (SBT08-003 to 007 and SBPP-062) and "Stretched at Prepreg Level" using one horizontal cross-bar.

16-ply prepreg stacks were stretched individually and then combined to make the QI 32-ply lay-up stacks prior to autoclave cure. Due to dimension limitations, just two (2) CAI test coupons could be cut from one cured SBPP panel. Thus, each "SBPP" data point in Figure 15, representing the average of four (4) test replicates, required an initial two (2) panels.

CAI strength test results are consistent with the data obtained from the ±45° and QI 16-ply panels. Compared to the controls, CAI strength was higher when the test load was parallel to the stretch direction and was lower when the test load was perpendicular to the direction of stretch.

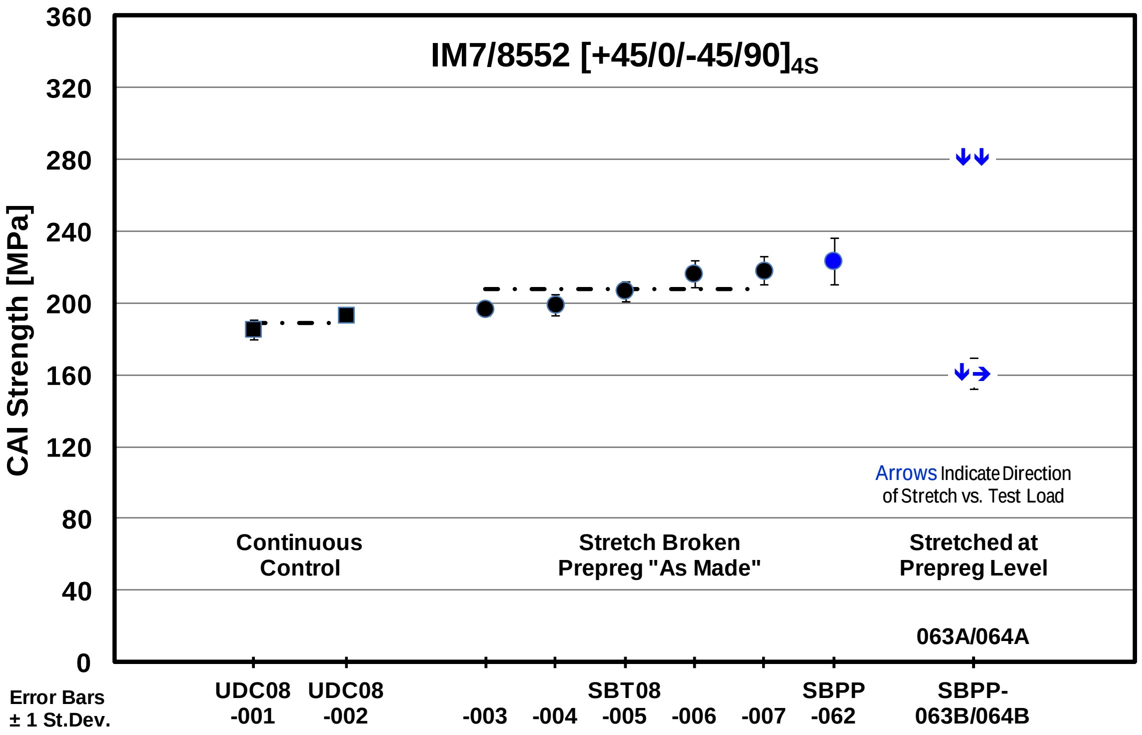


Figure 15: Comparison of Compression after Impact Strength of Continuous IM7/8552, Stretch Broken “As Made, and Stretched at Prepreg Level (by overall 10%)

4. DISCUSSION

For properties derived from a prestretched uni-axial lay-up (with 10% overall stretch) such as Tensile and SBS strength, there is little apparent effect of stretching. For in-plane shear strength, the effect is more apparent.

In IPS, when tested parallel to the stretch direction, strength appears to increase relative to the “As Made” material. When tested perpendicular to the stretch direction, IPS strength appears to decrease. These results already account for the angle changes using the modified ASTM D 3518 procedure described in 3.1.1.2.

This procedure uses the Maximum Stress failure criteria, which only considers the ply in-plane shear when attributing laminate (coupon) failure. This is a reasonable assumption for a ±45° lay-up, as defined in the test standard.

In reality, there are three stresses that contribute to ply failure: 0° (axial) ply stress, 90° (transverse) ply stress, and ply in-plane shear. A combined failure criterion such as Tsai-Hill considers all stress contributions to failure, whereas the Maximum Stress failure criteria only considers one – the stress closest to failure (i.e. the stress component with the lowest margin of safety).

It can be shown that, for the case of IPS tests perpendicular to the stretch direction, the ply IPS stress contributes about 60% of the Tsai-Hill failure index, where 100% represents failure. For

IPS tests parallel to the stretch direction, the ply IPS stress contributes about 80% of the Tsai-Hill failure index. This remains to be fully explored to determine its effect on reported IPS strength values for the stretched material.

4.1.1 Pre-Stretching Procedures

Methods have been developed to impart a known, controlled degree of stretching into a prepreg lay-up, representing the deformation the lay-up experiences when formed into a complex shape. It was determined that applying a normal force on the lay-up via vacuum bag during stretch helped stabilize the lay-up. Furthermore, using a series of clamping bars, lateral contraction of the prepreg lay-up due to Poisson effects can be more easily controlled.

4.1.2 Tension and Short Beam Shear Strength

The application of 10% overall stretch has very little noticeable effect on these properties.

4.1.3 In-Plane Shear

A modified ASTM D 3518 procedure was developed to account for lay-up angle changes during stretching. This procedure collapsed all IPS modulus data to a common value, indicating that stretching has no appreciable effect. For IPS strength, the procedure reduced the apparent variation across the panel width due to angle effects. It also reduced the spread between IPS strength for As-Made material and material tested either parallel or perpendicular to the stretch direction. However, there remains a relatively large difference between these strength values. While there are possible explanations for this apparent discrepancy, further examination would be required.

4.1.4 Quasi-Isotropic Lay-up – Bearing, OHT, OHC, CAI

Bearing Response, Open Hole Tension, and Compression property tests were performed on quasi-isotropic lay-ups. As noted, the original ±45 plies deform during stretching such that the stretched laminate, after cure, no longer has [0/±45/90] orientation. This changed the reported property value, but does not mean that the inherent property of the material has been degraded.

There are several ways to address the lay-up angle change, so that a given property (CAI, for example), may be evaluated in the pre and post stretched condition to determine if the stretching operation actually causes property changes in the material itself. One method, though laborious, is to measure the as-formed lay-up angles after stretching, and to then lay up, cure and test panels made from As-Made material in the same laminate configuration. This allows a more meaningful comparison of properties and to determine the effect, if any, on material properties.

5. CONCLUSIONS

It is apparent from this work that even relatively straightforward forming scenarios such as uni-axial stretching of basic SBCF prepreg lay-ups creates thickness and lay-up angle changes in the formed and cured part. Lay-up changes due to forming are highly dependent upon fiber orientation and laminate makeup, which can vary widely in different structural applications. To design and analyze the properties of the formed laminate, it is important to understand the changes in ply angles and thickness when forming parts.

For some properties such as Tension and SBS, testing of pre-stretched SBCF material indicated that no significant degradation results from the forming operation within the investigated stretch ratio. In other cases, property changes are observed, both increases and decreases. Further work is required to determine whether these property changes are attributable to actual changes in the material itself, changes in laminate orientation that occur during forming, or a combination of these effects.

6. ACKNOWLEDGEMENTS

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