PROCESS DEVELOPMENT AND CHARACTERIZATION OF STRETCH BROKEN CARBON FIBER MATERIALS

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ABSTRACT

Interest in aligned discontinuous fiber materials has increased significantly in recent years as they facilitate new and more cost effective forming techniques for complex shaped composite parts compared to continuous fiber systems.

This paper presents results on key parameters of the stretch break process to enhance the formability of Stretch Broken Carbon Fiber (SBCF) materials, in particular of intermediate modulus carbon fibers, and their characterization at the tow and prepreg level.

1. INTRODUCTION

Prior work conducted in Hexcel's Navy-funded SBCF program has been published at the 2005, 2006, and 2007 SAMPE spring conferences. Characterization of the SBCF materials included the development of a formability test method for resin impregnated SBCF materials, also applied to resin impregnated SBCF materials produced with different break lengths [1-5].

Initial mechanical performance testing has been conducted on composites reinforced with both stretch broken (SB) and continuous carbon fiber [1,2,5]. Mechanical performance test results of a comprehensive range of properties are being published [6].

Previous program work had as one of its goals to provide a quality control test for Hexcel's SBCF tows that can be performed routinely and expeditiously. Ideally, this test method should be performed on the unaltered SBCF product, i.e. as made sized stretch broken tow. Among several techniques evaluated, a modified dry tow tenacity test showed promise compared to the labor intensive single filament test method [5,7].

This paper describes recent improvements made in the stretch breaking process that have led to enhanced formability of stretch broken intermediate modulus carbon fiber materials through further reduction of the average filament break length as well as break length variability. Also discussed are further developments and improvements in the use of an elevated temperature dry tow tenacity (ETDTT) test as a quality control tool for SBCF tows.

2. BACKGROUND

The range of complex shaped parts that can be made by conventional double-diaphragm forming techniques is limited due to the specific constraint imposed by continuous fibers. The inextensibility of the continuous reinforcement drives the deformation behavior of the material during the forming process. Since the continuous filaments in the tow cannot stretch, deformation is achieved either by intraply-shearing perpendicular to the fiber z-axis or through an interply shearing mechanism. For complex part geometries, however, interply shearing often results in wrinkling of the plies in the laminate.

The ability of stretch broken carbon fiber to stretch in the fiber direction, due to the discontinuous nature of the filaments, allows successful forming of a ply stack without large amounts of interply shear. This offers the potential to fabricate a greater range of complex geometries, thereby eliminating costly hand lay-up operations. If for certain part geometries the forming step results in compressive strains in the ply stack, wrinkling will occur. For such geometries, SBCF materials would not provide any benefits. Appropriate part configurations have to be identified and selected to take advantage of the enhanced formability of SBCF materials (and other aligned discontinuous fiber materials).

Hexcel Corporation has been working on the development of stretch broken carbon fiber since the late 1990s and has invested a large amount of internal funding and effort. Initial development work utilized a commercially available textile-based stretch break machine. Modifications to the machine and continued process development led to a unique stretch-broken carbon fiber tow that consists of aligned, randomly broken filaments that, through application of thermoset sizing resins, can be processed in an identical fashion to standard continuous filament tow. Due to the random nature of the filament breaks and the filament length being larger than the critical fiber length, resultant mechanical properties are nearly equivalent to those of composites fabricated with continuous reinforcement.

The starting material for Hexcel's stretch breaking process can be any unsized carbon fiber tow. However, all of the previous work and the present study utilized Hexcel's AS4 and IM7 fiber, which have been qualified, with Hexcel's GP sizing, for numerous DoD programs. The qualification status of the base fiber and GP sizing as well as the feasible utilization of qualified resins generated Navy interest and support for further development and characterization of stretch broken materials with a view toward transitioning to DoD programs.

A multi-year research and development program started in FY 2002 focused on developing the SBCF-based material forms and demonstrating lower cost processes that might be used to form complex shaped composite structures. In the initial two program years, mainly formability and forming processes were explored using SBCF materials made on a textile-based stretch break machine. It was shown that material with an average broken filament length of approximately 10 cm (4 inches) allows forming into complex shapes that are not possible with continuous carbon fiber. However, limitations were found when increasing the complexity of shaped parts in forming trials using conventional, low cost, double diaphragm composites forming technology.

It then became clear that an average broken filament length of less than 10 cm would enhance formability and improve conformance of complex shaped parts. Given the constraints in design of the textile-based equipment, a second generation stretch break (SB2) machine was designed to produce stretch broken carbon fiber tow with average broken filament lengths of significantly less than 10 cm. The SB2 Machine became operational in May 2006 and produced the Generation 2 stretch broken carbon fiber material of "shorter" broken filament length for the NAVAIR funded program. Most, if not all of the program utilized Gen 2 SB AS4 fibers, which exhibit an average broken filament length of approximately 7 cm. This shorter broken filament length significantly improved formability of Generation 2 SBCF materials (AS4 with the 8552 resin), allowing the manufacture of bead-stiffened panels of high conformance [8].

The current Navy-funded program (awarded at the end of December 2007) targets technology demonstrations that could benefit Navy aircraft programs, for which IM7/8552 is the fiber/resin system of choice. SB IM7 materials are more difficult to form than those made from AS4 fiber, a result of the smaller IM7 filament diameter (5 µm versus 7 µm for AS4) and associated increased surface energetics. The SB2 Machine was designed to produce SBCF at an average broken filament length as short as 5 cm (2 inches). This can be accomplished by reducing the spacing of the break zones. Typically, the average broken filament length is similar to the spacing of the two break zones. Modifications to the break system, which became necessary to enhance stiffness, limited the break zone spacing to 7.30 cm (2 7/8 inches).

One of the current program's goals is providing stretch broken IM7 based materials that are equivalent to Gen 2 SB AS4 materials in terms of formability. This can be accomplished by (a) increasing the resin content or (b) reducing the average broken filament length of IM7. Since increasing the resin content would be harmful to mechanical performance, efforts were focused on reducing the break zone spacing. Recent modifications to the SB2 Machine allowed spacing of the break zones as small as 5.08 cm (2.0 inches) each.

3. EXPERIMENTATION

3.1 Stretch Breaking of Carbon Fiber

AS4 12K and IM7 12K were used as feed fiber to manufacture the stretch broken carbon fiber materials. Hexcel proprietary operating procedures were applied.

3.1.1 Generation 1 SBCF Tows

A textile-based stretch break machine, Seydel Model 682, was utilized to manufacture the Generation 1 (Gen 1) SBCF tows at the (fixed) spacing of the 2 break zones of 10 cm each.

The designation of the Generation 1 SBCF tows is "Gen 1 SB AS4-GP 12K" or "Gen 1 SB IM7-GP 12K".

3.1.2 Generation 2 SBCF Tows

The Generation 2 Stretch Break Machine (SB2 Machine) was utilized to manufacture the Generation 2 SBCF tows at the spacing of the 2 break zones of 7.3 cm (2 7/8 inch) each.

The designation of the Generation 2 SBCF tows is "Gen 2 SB AS4-GP 12K" and "Gen 2 SB IM7-GP 12K", respectively.

IM7 12K fiber, stretch broken at the shorter break zone spacing of 5.08 cm (2.0 inch) each, is designated SB (2.0”) IM7-GP 12K.

3.2 Broken Filament Length

Determination of the broken filament length followed ASTM D 5103 “Standard Test Method for Length and Length Distribution of Manufactured Staple Fibers (Single-Fiber Test)”. Typically, the lengths of 200 filaments were measured, carefully pulled from a never-sized SBCF tow.

3.3 Elevated Temperature Dry Tow Tenacity (ETDTT)

Testing of the Dry Tow Tenacity was performed at Advanced Fiber Technologies, Inc. according to Hexcel’s proprietary testing procedure, but at elevated temperature on sized SBCF tows. Parameters such as temperature and test gage length were developed in order to obtain meaningful results from the ETDTT testing.

3.4 Manufacture of UD Prepreg Tapes

The so-called Witness Tape Line was used to manufacture 300mm wide UD prepreg tapes from Gen 1 and Gen 2 SB AS4 and IM7 fiber. Commercial prepreg lines at Hexcel Matrix SLC were used for all SB (2.0”) IM7-GP 12K.

3.5 Prepreg Formability

Formability characterization utilized a multi-axial or ‘bulge’ testing device, developed and fabricated at PennState University’s Applied Research Laboratory in collaboration with Hexcel and Northrop Grumman [4]. This test unit is comprised of a 25.4 cm diameter pressurization chamber, above which a layer of high temperature bagging material and the test ply stack is clamped in place using a serpentine cross section ring and eight bolts. The ring was grit blasted to prevent sample slippage. A linear variable displacement transducer is placed at the center of the sample along with a control thermocouple. Heat is applied using a heat gun that is connected to a controller, and pressure is set to a desired level (up to 0.1 MPa), applied by opening a valve to admit air to the shallow pressurization chamber. Temperature and central displacement values are captured using a data acquisition system.

4. RESULTS

Recent modifications to the SB2 machine to shorten the spacing of the break zones were implemented in a step-by-step approach. In the first step, the break zone spacing was reduced to 5.72 cm (2 ¼ inch) from the setting of 7.3 cm (2 7/8 inch) applied to the SBCF tows broken for the previous effort. After improved formability of the SBCF materials of shorter filament length was demonstrated (see below), the break zone spacing was reduced to 5.08 cm (2.0 inch), the shortest setting possible given the design of the SB2 machine. Certain modifications were necessary to maintain stiffness of the break stations while allowing the break zones spacing of 5.08 cm (2.0 inches).

The break zones spacing of 5.08 cm (2.0 inches) was successfully applied to stretch breaking of IM7 12K and IM7 6K tows. Limited experience indicates that AS4 6K tows also can be processed at this setting. However, AS4 12K tows could not be processed at either 5.72 cm (2 ¼ inch) or 5.08 cm (2.0 inches) break zone spacing. This can be explained by the much higher amount of energy generated to break 12,000 AS4 filaments of 7 µm in diameter compared to the 5 µm IM7 filament diameter. As the fracture energy propagates, the filament will again break at a “weak spot”, causing short filament fragments and deteriorating the tow bundle integrity.

4.1 Broken Filament Length Distribution

The length of the broken filaments and its distribution was determined on SB (2.0”) IM7-GP 12K, in comparison to the previously published data obtained from Gen 1 and Gen 2 SB AS4 12K fiber [5].

The Figure 1 compares the filament length distribution of the SBCF tows manufactured at the different break zone settings. The Gen 1 AS4 data set consists of 200 data points, the Gen 2 AS4 of 2 x 200 data points, and the SB (2.0”) IM7 of 4 x 200 data points.

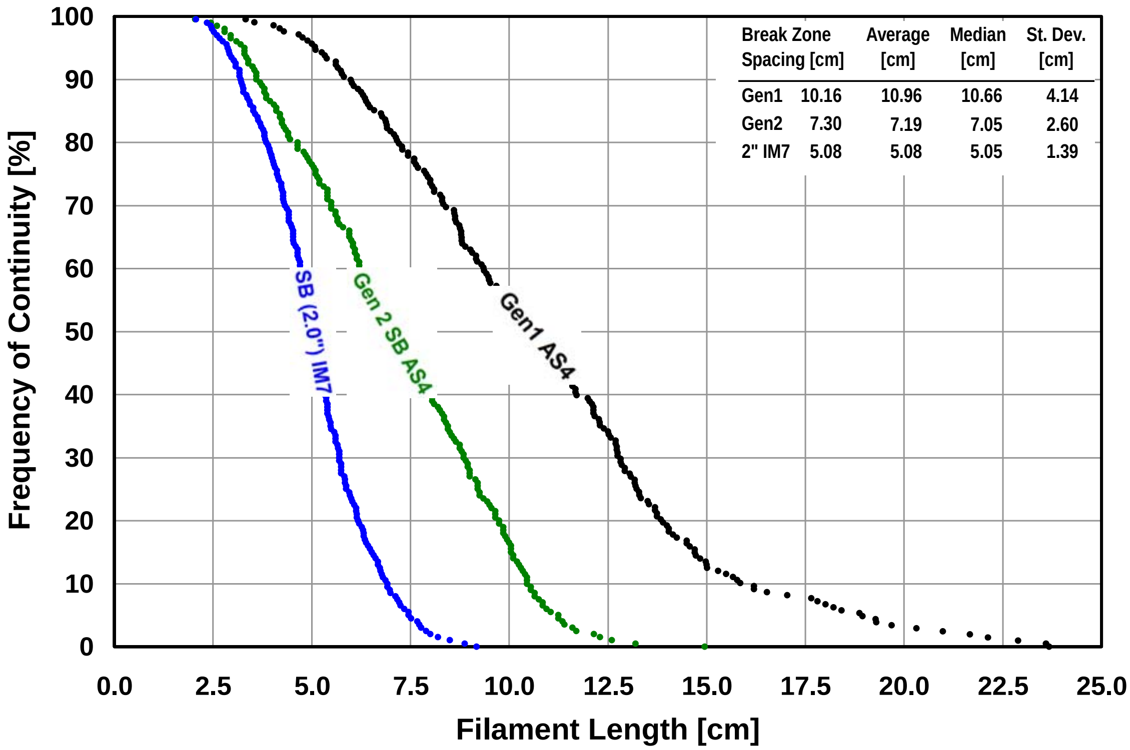

Figure 1: Frequency Distribution of Broken Filament Length of SBCF Tows Manufactured at Different Break Zone Spacing

The results obtained from this optical determination indicate that average filament length of a SBCF tow corresponds approximately to the break zone spacing. It is also apparent that the distribution of the filament length is narrower the shorter the break zone spacing.

One should expect better formability of SBCF prepreg materials made at shorter break zone spacing, assuming same filament diameter, resin content and viscosity. In addition, the absence of “long” filaments should ease forming of complex shaped parts with sharp curvatures.

Experience has shown that the determination of broken filament length by optical measurement and counting following AST D5103 can be quite variable. This method may be useful as a baseline method, although the quality of results strongly depends on skill, expertise and excellent vision on the part of the experimenter.

4.2 Elevated Temperature Dry Tow Tenacity (ETDTT) Tests

Due to the disadvantages of the method by optical measurement and counting, alternative techniques have been investigated for evaluating the quality of SBCF tows [7]. Two new techniques were recognized (resonant frequency and modified dry tow tenacity) that show promise compared to the labor intensive single-fiber test method. More recent studies on Generation 2 SBCF tows resulted in the expected response of much lower peak loads in the dry tow tenacity test compared to Generation 1 SBCF tows [5].

Since handling of unsized SBCF tows is difficult, efforts focused on the development of a test method that could be performed on the unaltered SBCF product, i.e. sized, stretch broken tow as made and taken up in the SBCF process. At room temperature, the sizing acts as a binder, making the appearance of a sized SBCF tow indistinguishable from a standard carbon fiber tow. At elevated temperatures however, the viscosity of low-molecular weight epoxy-based sizing is reduced, changing the sizing's characteristic to a lubricant, allowing the broken filaments to slide along each other under tension.

At a given elevated temperature, the load response should be a function of the specimen gage length for a given average broken filament length, or vice versa, a function of the average broken filament length for given specimen gage length. At a given average broken filament length (and constant gage length), the load response should increase with wider distribution of filament length.

4.2.1 Initial ETDTT Tests

In an initial investigation of proof of concept, Gen SB IM7-GP 12K tows, broken at 7.30 cm break zone spacing, were tested under tension at elevated temperatures and various specimen gage lengths. As Figure 2 shows, the peak load at 5.08 cm specimen gage length is flat, which is no surprise since one can anticipate that approximately 75% of the filaments are continuous (see Figure 1). With increased specimen gage length (Figure 3), the peak load decreases as the ratio of continuous filaments decreases. A slight influence of the test temperature on the peak load can be observed for the specimen gage lengths, slight because of the investigated temperature range. For comparison, the peak load measured at room temperature ranges between 300 and 400 N.

Based on this load response behavior, a test temperature of 100 °C and a specimen gage length of 7.62 cm (3.0 inch) were considered for the characterizing SB (2.0") IM7-GP 12K tows. In a larger test series, 4 sets of 10 specimens each, SB (2.0") IM7-GP 12K tows were compared to Gen 2 SB IM7-GP 12K tows. Peak loads for this test series are shown in Figure 4. The average peak loads reflect well the two materials: The SB (2.0") IM7-GP 12K tows, broken at the shorter break zone spacing of 5.08 cm, have the expected lower peak load response of 30 N compared to 60 N for the Gen 2 SB IM7-GP 12K tows, broken at a break zone spacing of 7.3 cm. This load response difference is to be contributed to the higher ratio of continuous filaments in the Gen 2 SB IM7-GP 12K tows at this test gage length.

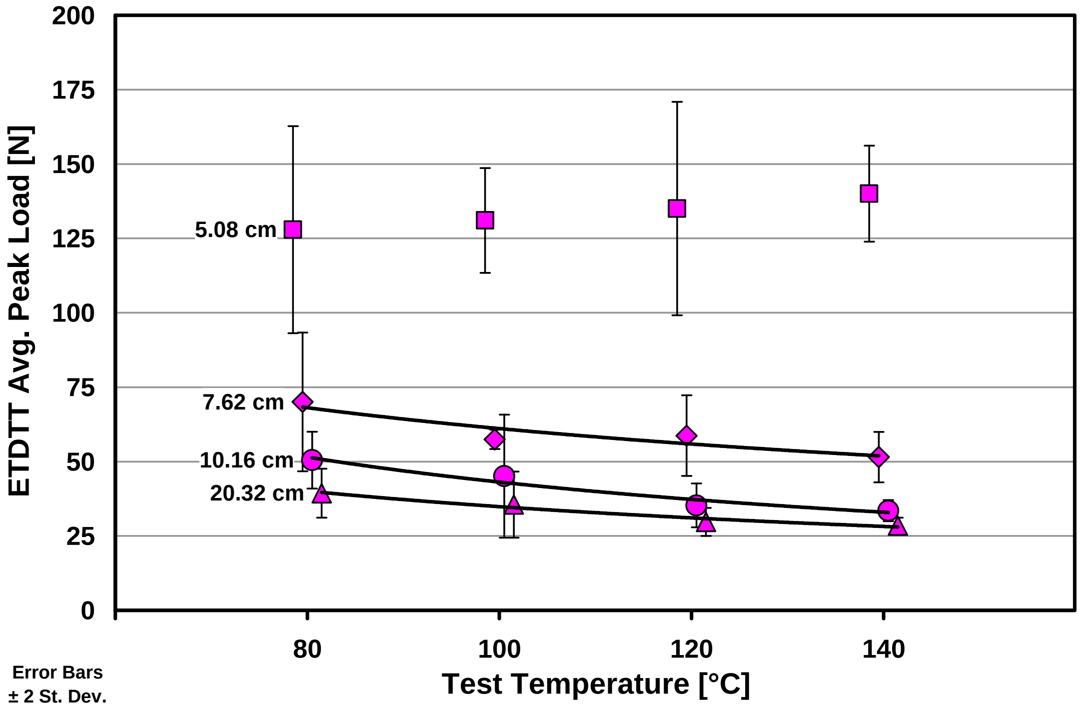

Figure 2: ETDTT Peak Load of Gen 2 SB IM7-GP 12K tows (7.3 cm break zone spacing) versus Test Temperature for Test Gage Lengths Varying from 5.08 cm to 20.32 cm

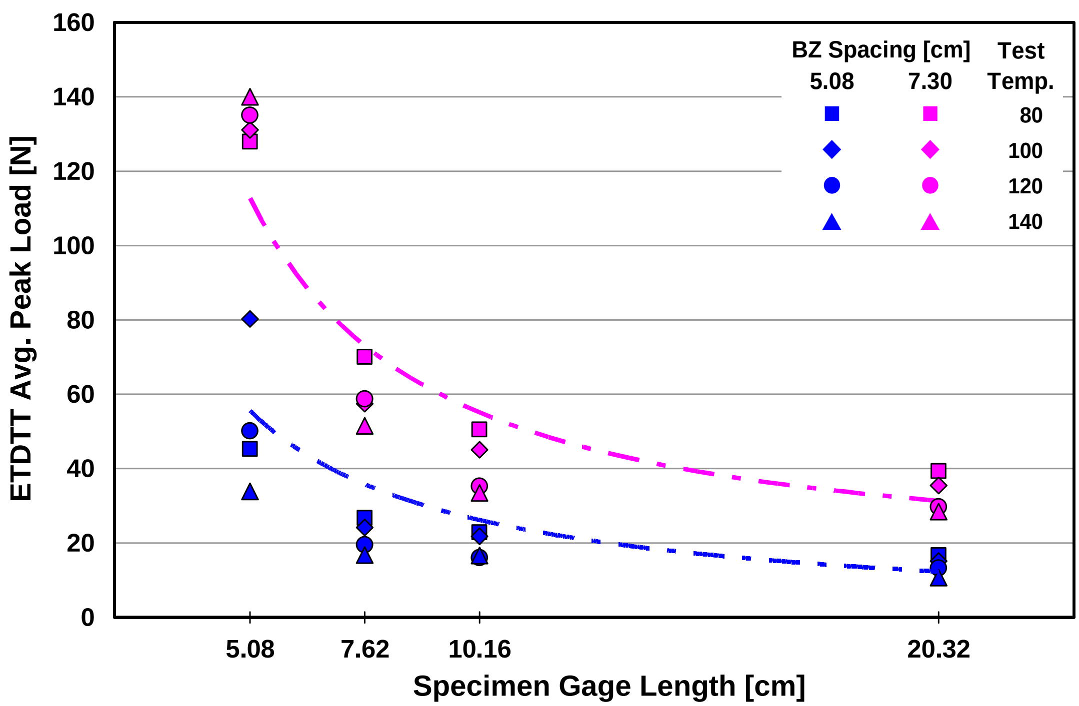

Figure 3: ETDTT Peak Load of SB IM7-GP 12K tows (5.08 cm and 7.3 cm break zone spacing) versus Test Gage Length for Temperatures Varying from 80 °C to 140 °C

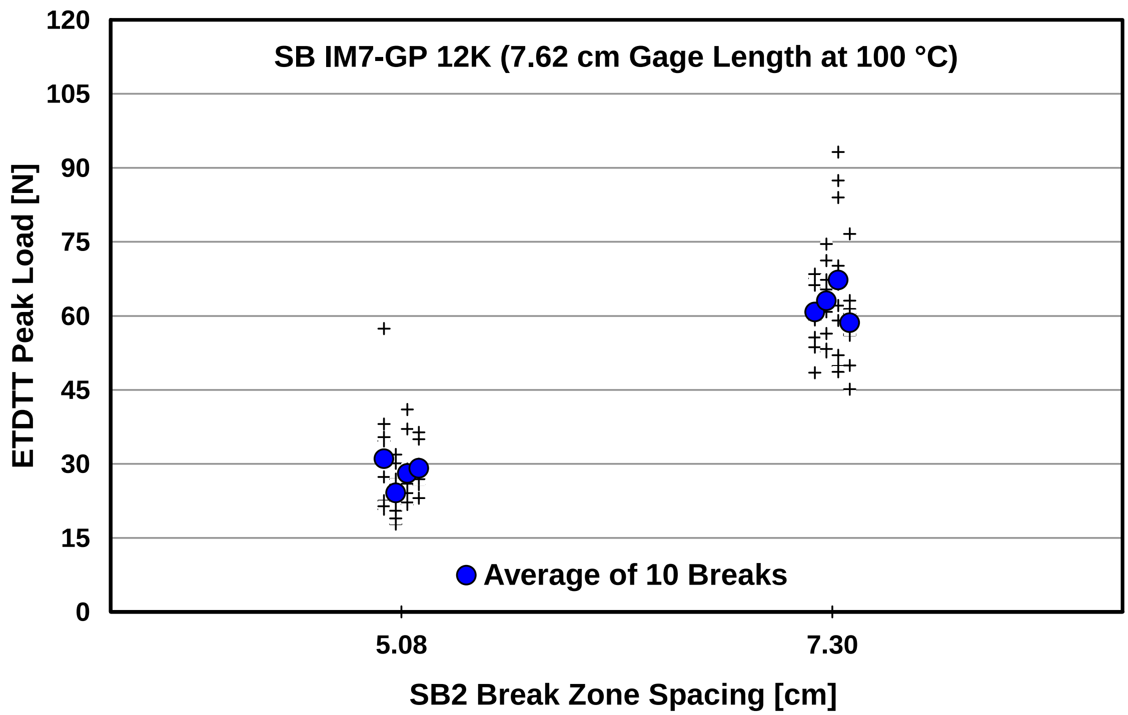

Figure 4: ETDTT Peak Load of SB IM7-GP 12K tows – Broken 5.08 cm and 7.30 cm Break Zone Spacing

4.2.2 ETDTT Studies on Stretch Break Process Parameter Variations

After demonstration that the Dry Tow Tenacity at the Elevated Temperature of 100 °C and a specimen gage length of 7.62 cm (1.5 X of the break zone spacing of SB (2.0”) IM7-GP 12K) could discern differences between SB IM7-GP 12K made at different break zone spacing, these conditions were applied for the following test series. For the further investigation of the ETDTT, parameters of the stretch process were varied with the expectation that these variations will produce SBCF tows of different “quality”. The average length of the broken filaments and the length distribution are probably the most important quality characteristics of SBCF tows, considering formability of SBCF materials.

Of the many stretch break process parameters, variations of the overall process stretch, the feed tension, and the nip roll pressure were chosen to provide out-of-standard materials for characterization in the ETDTT test.

4.2.2.1 Variation of Stretch Break Process Stretch Ratio

In a trial series, the overall stretch break process was reduced in five increments to 36% of the standard overall process stretch. It was expected that this would lead to SBCF Tows of varying degrees of average broken filament length and broken filament length variability. At lower overall stretch ratios, it might be expected that the average peak load would be higher than at higher stretch ratios, since there should be a greater percentage of continuous filaments. Also, the variability should be greater, since there is less likelihood of exceeding the strain required to break most or all of the filaments.

Figure 5 below shows the average peak load and the variability (as CV) at each process condition.

The peak load decreases as process stretch increases up to ~ 70% of Standard, when it appears the peak load levels out. This would suggest the SBCF has reached its maximum in filament break efficiency and the average peak loads noted (20 to 40 N) are in the same range as standard SBCF samples.

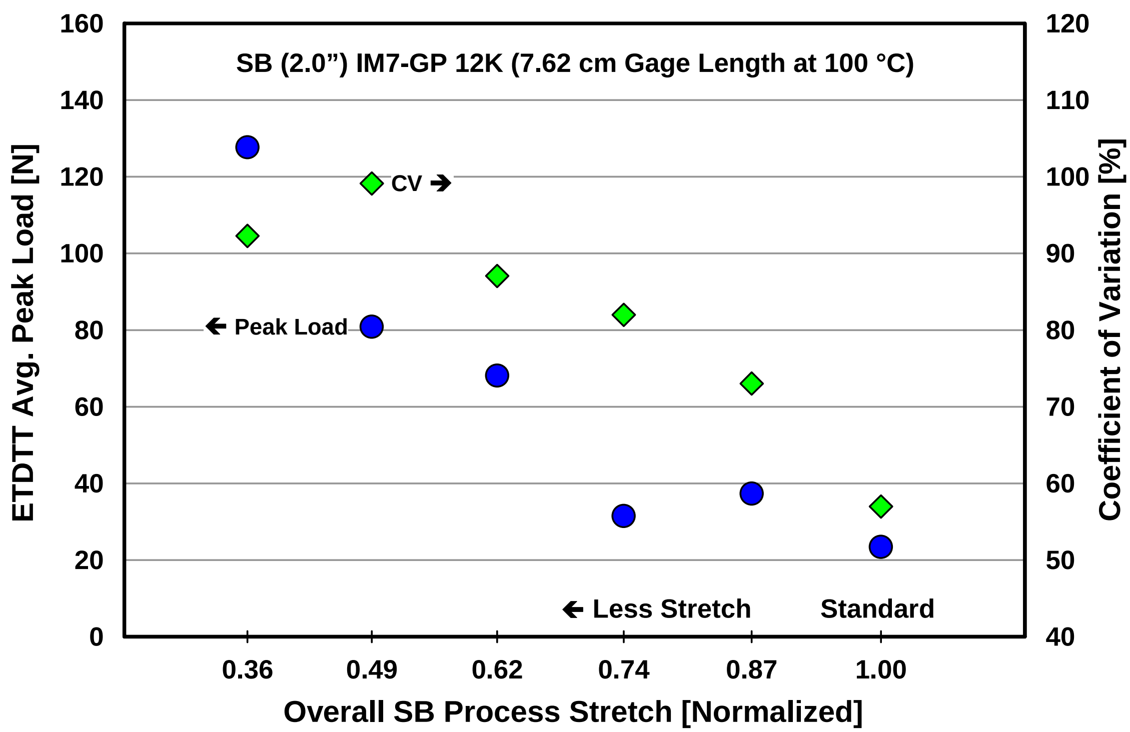

Figure 5: ETDTT Tests of SB (2.0”) IM7-GP 12K: Peak Load and Peak Load Variability as Function of Process Stretch (2 spools, 36 breaks per data point)

For the CV obtained, there appears to be a definite trend toward lower variability at higher process stretch, which again makes sense as one would expect a more complete and uniform breaking of the individual filaments at higher stretch ratios.

4.2.2.2 Variation of Stretch Break Feed Tension

The wider the tow is pre-spread, when entering the first break station, the greater the number of filaments will be clamped by the nip rolls, leading to a uniform stretch and increased probability that filaments are broken when passing the first break station.

The width of the (unsized) carbon fiber tow can be adjusted by guiding the tow(s) through a spreader bar arrangement. The higher the tow tension at the inlet – limited by tow damage, the wider the tow will be spread.

In a trial series, the tension of the tow coming off the creel was varied over a range that was determined by operability towards lower tension and tow cosmetics (damage) towards higher tension, compared to standard tensioning.

Figure 6 below shows the average peak load and the variability (as CV) at each process condition. Originally, lower feed tensions than 0.63 of standard were planned for this trial series, but operability deteriorated dramatically, such that just one spool could be manufactured at 0.63 of standard, despite multiple attempts.

If there is any effect of the feed tension on peak load, it is small for the investigated range of feed tension. Differences in beak load between these feed tension conditions are hardly discernible.

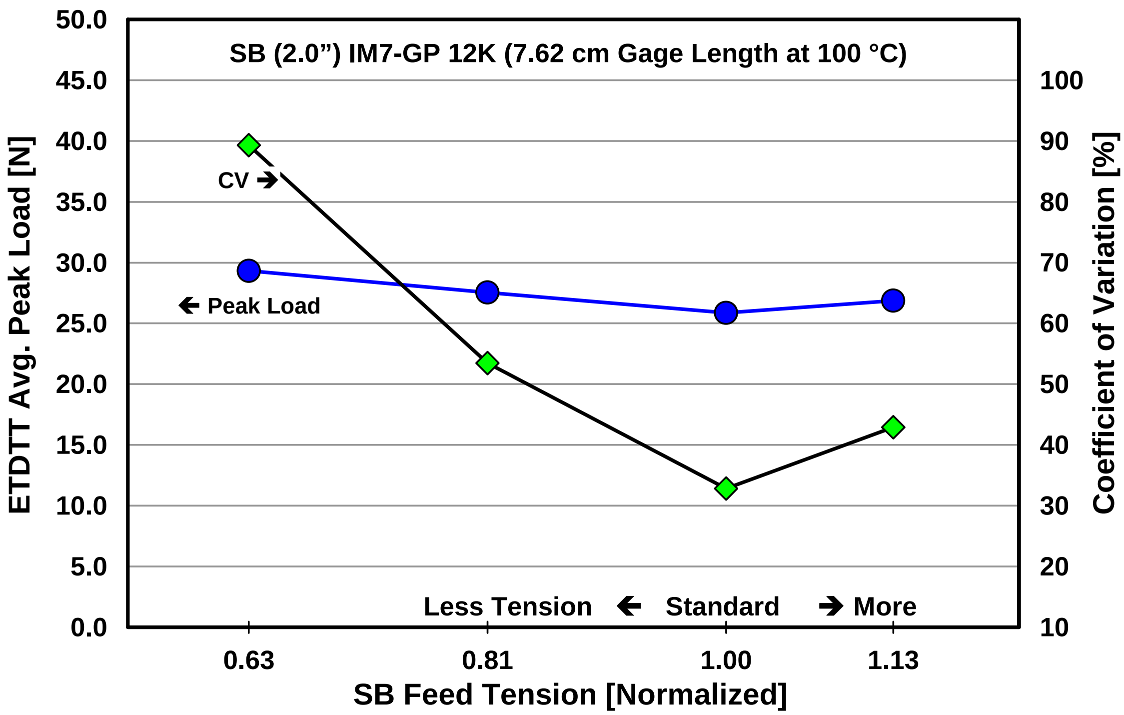

Figure 6: ETDTT Tests of SB (2.0") IM7-GP 12K: Peak Load and Peak Load Variability as Function of the Feed Tension (2 spools, 40 + 30 breaks per data point, except for 0.63 of Standard: 1 spool, 40 breaks per data point)

However, the data suggest an effect of feed tension on data variability, which should correlate to SBCF quality or reproducibility with poorer quality expected at lower feed tensions. The lowest variability was obtained around standard process setting for feed tension. It should be noted that the tow cosmetics at 1.13 of standard were inferior to standard feed tension.

4.2.2.3 Variation of SB Nip Roll Pressure

As adequately adjusted feed tension is one parameter to SBCF quality, the level of the nip roll pressure of the break stations is another variable in the stretch break process. It would be expected that at higher pressures the likelihood for the filaments in the tow bundle to slip is reduced and filament breaks should be more uniform, resulting in a SBCF tow of higher quality. On the other hand, too high a pressure could damage the tow, deteriorating tow quality by poor cosmetics.

In a trial series, the nip roll pressure was varied by reducing the nip roll pressure in five increments from standard. A higher-than-standard pressure was not attempted since bearings are at their design load limit. Figure 7 below shows the average peak load and the variability (as CV) at each process condition.

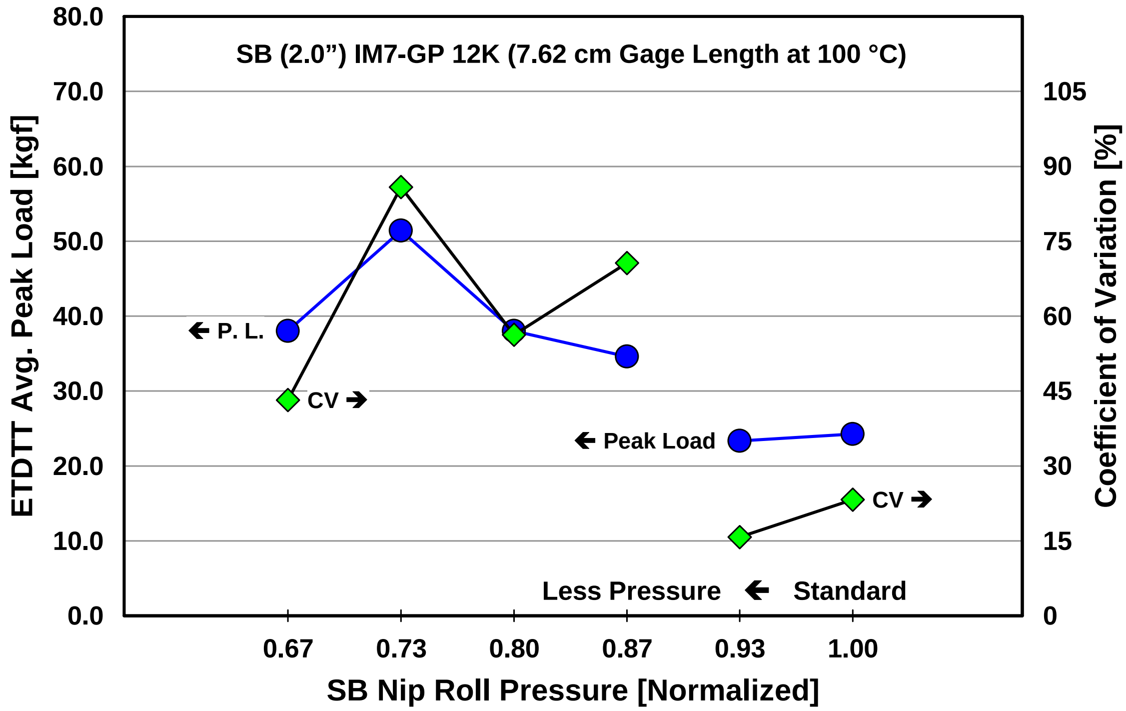

Figure 7: ETDTT Tests of SB (2.0") IM7-GP 12K: Peak Load and Peak Load Variability as Function of the Nip Roll Pressure (2 spools, 24 breaks per data point)

The data suggest a trend toward lower peak load and lower variability at higher nip roll pressure, with a possible step change at the higher nip roll pressures, 0.93 of standard and standard.

All of the data obtained to date suggest the ETDTT test could prove a useful tool for monitoring the quality of the SBCF product.

4.2.3 Prepreg Formability Studies (Bulge Testing)

The multi-axial or 'bulge' testing device has been proven to be a useful tool to gain information on the formability of prepreg materials made from SBCF [4,5]. Previous studies have shown that the displacement behavior of SBCF prepregs depends on various parameters. Primary bulge testing parameters are temperature, pressurization, and final pressure, assuming clamping diameter is unchanged (constant). Variables contributed by the SBCF prepreg materials are broken filament length, filament diameter (AS4, IM7), resin type, and the thickness of the prepreg stack.

When investigating the bulge test as a tool to characterize SBCF prepreg formability, testing parameters should be kept constant to allow comparison between the various SBCF prepreg materials. After review of previous bulge test parameters and displacement curves, a testing temperature of 100 °C (212 °F) was chosen, close to temperatures when forming parts. A pressure of 0.1 MPa was chosen, which is equivalent to the pressure level in vacuum forming processes. This temperature/pressure combination allows running most of the materials in the bulge test for 30 minutes. The test was terminated after 30 minutes or when the displacement reached approximately 10 cm, whichever event occurred earlier.

4.2.3.1 Pressurization

Previous tests and also initial for this effort had the pressure instantaneously applied at the start of the test by opening a valve to admit air to the shallow pressurization chamber. Typically, the target pressure, here 0.1 MPa, is reached within approximately ten (10) seconds.

Figure 8 below shows the displacement curves of Gen 2 SB AS4/8552 and Gen 2 SB IM7/8552 prepregs when the pressure of 0.1 MPa is applied instantaneously at the beginning of the test. It is apparent that prepregs with SB AS4 reinforcement are more easily formable than prepregs with SB IM7 reinforcement, a (known) result of the smaller IM7 filament diameter (5 µm versus 7 µm for AS4).

With the given clamping diameter of 25.4 cm, a displacement of 2.5 cm each corresponds to approximately 10 % stretch, neglecting edge effects due to clamping. When forming bead-stiffened panels [8] for instance, the SBCF prepreg materials will be stretched by approximately 5% to 15%. These stretch ratios correspond to bulge test displacement values of up to 4 cm. As the displacement curves in Figure 8 show, initial differences between the two SBCF reinforcements are minor.

In an attempt to obtain more quantifiable differences between different materials, the pressure was applied in increments to "slow down" the displacement in the early stage of the test. After application of 0.02 MPa (3.0 psi) at the beginning of the test (t=0), the pressure was increased in 0.007 MPa (1.0 psi) increments. The final pressure of 0.1 MPa is reached after 11:30 minutes.

Figure 9 below shows the displacement curves of Gen 2 SB AS4/8552 and Gen 2 SB IM7/8552 prepregs when the pressure is ramped to 0.1 MPa. The lower pressure at the beginning of the test results in a slower displacement, thus making the formability differences between the two SBCF reinforcements more distinguishable.

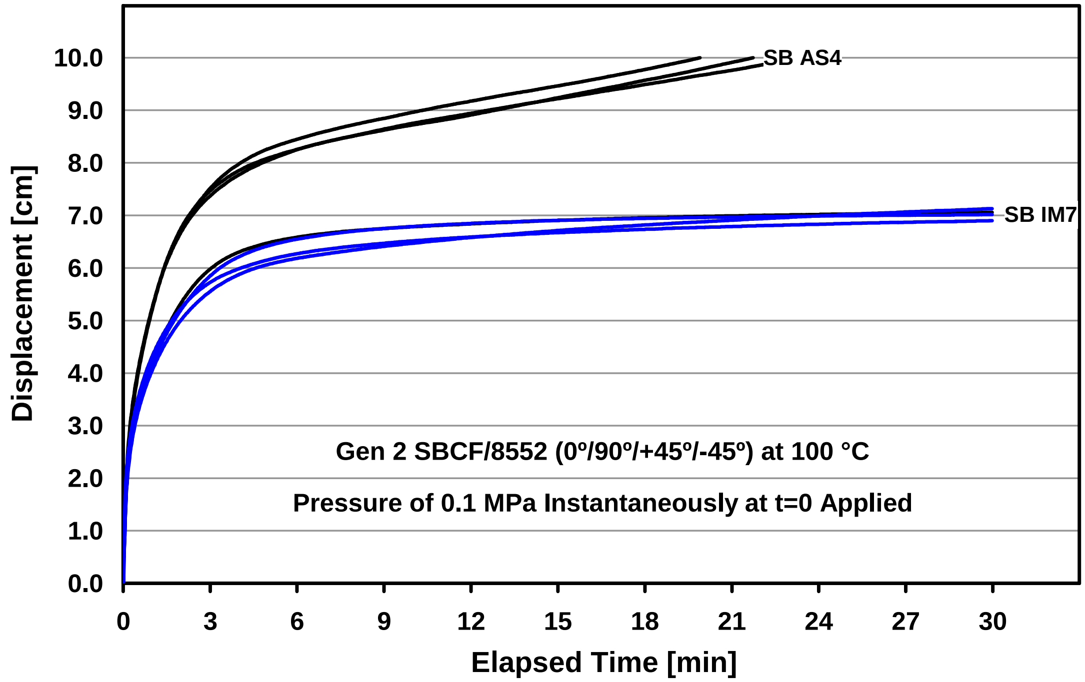

Figure 8: Bulge Test Displacement Curves of Gen 2 SB AS4/8552 (3 tests) and Gen 2 SB IM7/8552 (4 tests) Prepregs – Pressure of 0.1 MPa Instantaneously Applied

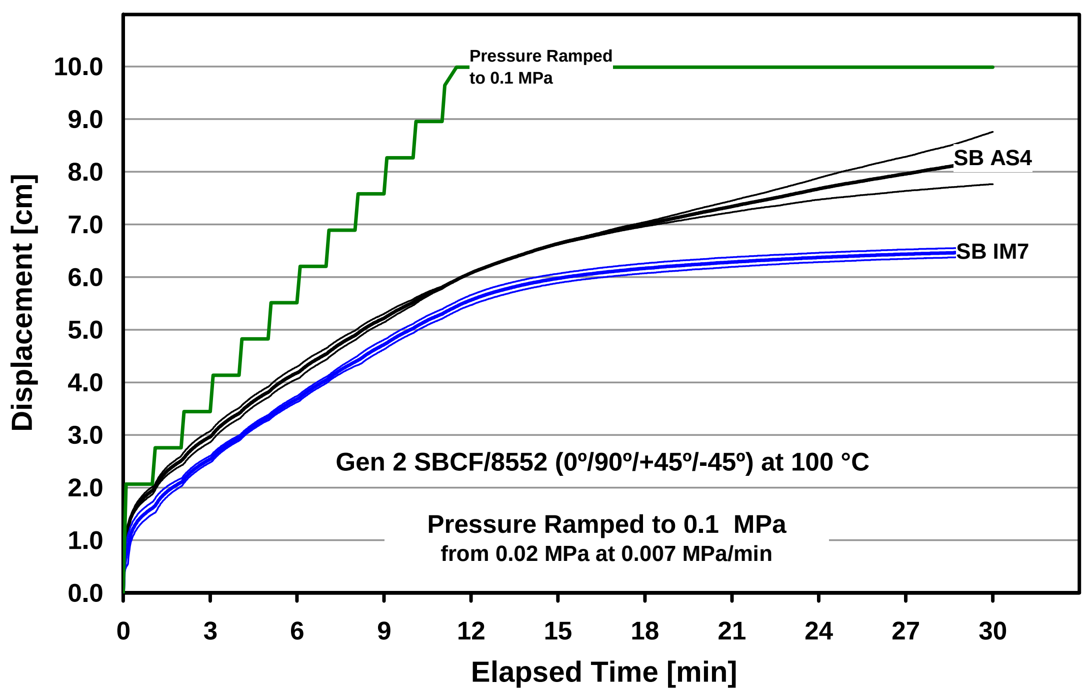

Figure 9: Bulge Test Displacement Curves of Gen 2 SB AS4/8552 and Gen 2 SB IM7/8552 Prepregs (2 tests each plus average shown) – Pressure Ramped to 0.1 MPa

4.2.3.2 Bulge Test Formability as Function of Broken Filament Length

One of the current program's goals is providing stretch broken IM7 based materials that are equivalent to Gen 2 SB AS4 materials in terms of formability. Reduction of the broken filament length of IM7 was accomplished by reducing the break zone spacing to as small as 5.08 cm (2.0 inches).

Figure 10 below shows the displacement curves for all generations of Hexcel's SBCF bulge-tested as 8552 prepregs.

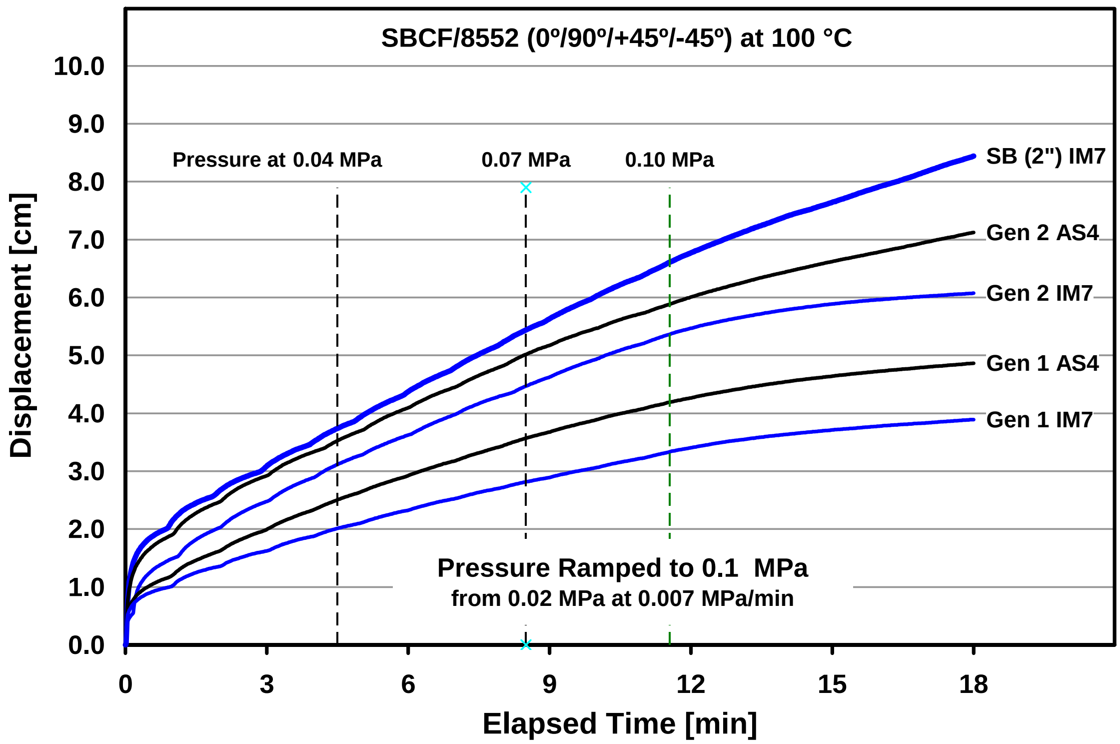

Figure 10: Bulge Test Displacement Curves of Gen 1 and 2 SB AS4/8552 prepregs and SB (2.0") IM7/8552 prepreg

As hoped for, the formability of the SB (2.0") IM7/8552 prepreg in the bulge test is at least equivalent to the Gen 2 SB AS4/8552 prepreg. The shorter average filament length (~ 5 cm) of the SB (2.0") IM7 fiber, compared to ~ 7 cm of the Gen 2 AS4 fiber, more than compensates for the smaller IM7 filament diameter and its associated increased surface energetics.

4.2.3.3 Bulge Test as QC Tool for SBCF Prepreg Materials

This encouraging result of SB (2.0") IM7/8552 prepreg formability led to the decision to go forward with the SB (2.0") IM7 fiber as reinforcement for forming trials within the Navy-funded SBCF program as well mechanical property characterization [5].

All SB (2.0") IM7/8552 prepregs manufactured at Hexcel Matrix were bulge tested in duplicates for formability. In order to allow comparison between the various batches, the "pressure ramped" variant of the bulge test was used.

Figure 11 shows the bulge test displacement measured when the pressure has reached 0.04 MPa, 0.07 MPa, and 0.10 MPa. Figure 10 above indicates when the displacement readings were taken for the chart in Figure 11. The prepregs designated SBT08-003 to SBT08-007 represent SB (2.0") IM7/8552 batches. For comparison, most left is the displacement shown for the Gen 2 SB IM7/8552 prepreg (nominal broken filament length of 7.30 cm). The second from the left, SB IM7 (5.72 cm) has SB IM7 reinforcement that was stretch broken at the interim break zone spacing of 7.72 cm (2 ¼ inch).

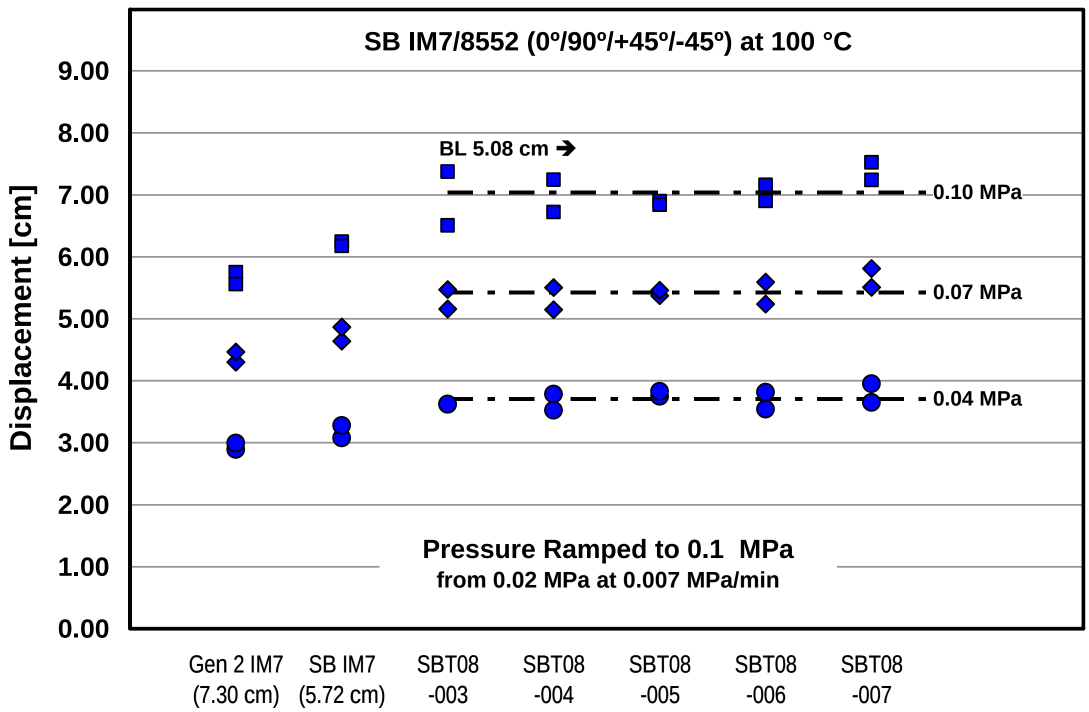

Figure 11: Bulge Test Displacement Readings at 0.04 MPa, 0.07 MPa, and 0.10 MPa for SB IM7/8552 prepregs (5.08 cm, 5.72 cm, and 7.30 cm stand for the nominal broken filament length.)

While the left part of the chart in Figure 11 supports the presentation of the improved formability with reduced broken filament length, the displacement data points for the five SB (2.0") IM7/8552 prepregs illustrate the low variability or consistency of the prepreg formability. CV values are 3.7%, 3.8, and 4.5% for the readings at 0.04 MPa, 0.07 MPa, and 0.10 MPa.

This way of presenting bulge test displacement data allows comparing SBCF prepreg materials, keeping track of possible trends, and identifying prepreg batches that are on the lower or higher side of formability.

5. CONCLUSIONS

The continued development of Hexcel's stretch break process led to stretch broken IM7 fiber with a shorter average broken filament length of approximately 5 cm and with improved formability in prepreg form.

All of the data obtained to date suggest the ETDTT test could prove a useful tool for monitoring the quality of the as manufactured SBCF product at the tow level. A correlation of the peak load data, averages and variability, with broken filament length distribution (see 4.1) is desirable, but would be a huge effort with questionable outcome, since the quality of results from the single filament test strongly depends on skill, expertise and excellent vision on the part of the experimenter.

The multi-axial 'bulge' testing device and testing procedures were further developed. Bulge testing results on SBCF prepreg materials confirm the improved formability of prepregs with stretch broken IM7 reinforcement of the short average broken filament length of approximately 5 cm. In addition, the bulge test could prove a useful tool for monitoring the quality of SBCF materials at the prepreg level.

6. ACKNOWLEDGEMENTS

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