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Blade System Design Study Part II: Final Project Report (GEC)

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Abstract

As part of the U.S. Department of Energy's Low Wind Speed Turbine program, Global Energy Concepts LLC (GEC)[1] has studied alternative composite materials for wind turbine blades in the multi-megawatt size range. This work in one of the Blade System Design Studies (BSDS) funded through Sandia National Laboratories.

The BSDS program was conducted in two phases. In the Part I BSDS, GEC assessed candidate innovations in composite materials, manufacturing processes, and structural configurations. GEC also made recommendations for testing composite coupons, details, assemblies, and blade sub-structures to be carried out in the Part II study (BSDS-II). The BSDS-II contract period began in May 2003, and testing was initiated in June 2004.

The current report summarizes the results from the BSDS-II test program. Composite materials evaluated include carbon fiber in both pre-impregnated and vacuum-assisted resin transfer molding (VARTM) forms. Initial thin-coupon static testing included a wide range of parameters, including variation in manufacturer, fiber tow size, fabric architecture, and resin type. A smaller set of these materials and process types was also evaluated in thin-coupon fatigue testing, and in ply-drop and ply-transition panels. The majority of materials used epoxy resin, with vinyl ester (VE) resin also used for selected cases. Late in the project, testing of unidirectional fiberglass was added to provide an updated baseline against which to evaluate the carbon material performance.

Numerous unidirectional carbon fabrics were considered for evaluation with VARTM infusion. All but one fabric style considered suffered either from poor infusibility or waviness of fibers combined with poor compaction. The exception was a triaxial carbon-fiberglass fabric produced by SAERTEX. This fabric became the primary choice for infused articles throughout the test program. The generally positive results obtained in this program for the SAERTEX material have led to its being used in innovative prototype blades of 9-m and 30-m length, as well as other non-wind related structures.

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[1] GEC was acquired by the Norwegian foundation, Det Norske Veritas (DNV) in May 2008, forming a new entity known as DNV Global Energy Concepts Inc. For purposes of this report, the previous company name, GEC, is used.

Acknowledgements

The work in this report was completed by Global Energy Concepts (GEC) for Sandia National Laboratories under Sandia Purchase Order No. 136426. The author wishes to acknowledge the technical contributions to this project of Dr. John Mandell and Mr. Dan Samborsky at Montana State University; Dr. James Locke at Wichita State University; and Sandia Technical Managers Tom Ashwill, Herb Sutherland, and Daniel Laird, as well as other Sandia personnel. All of the resin-infused articles tested under this program were fabricated by TPI Composites in Warren, Rhode Island. GEC thanks TPI for lending their manufacturing expertise and technical support toward the success of this project.

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Nomenclature

Ex	longitudinal modulus (GPa)
Ey	transverse modulus (GPa)
GPa	giga-Pascals (10^9 N/m^2)
m	meters
MPa	mega-Pacsals (10^6 N/m^2)
N	Newtons force
R	fatigue load ratio (minimum/maximum)
T_g	glass transition temperature (°C)
ε	material strain (%)
γ_m	combined partial safety factor for materials
$\mu\varepsilon$	micro-strain (10^{-6} m/m)
ν_{xy}	major Poisson's ratio of laminate
σ	material stress (MPa)
υ_f	laminate fiber volume fraction

Section 1 - Executive Summary

As part of the U.S. Department of Energy's Low Wind Speed Turbine program, Global Energy Concepts LLC (GEC) has studied alternative composite materials, with an emphasis on carbon, for wind turbine blades in the multi-megawatt size range. This work is one of the Blade System Design Studies (BSDS) funded through Sandia National Laboratories.

The BSDS program was conducted in two phases. In the Part I BSDS, GEC assessed candidate innovations in composite materials, manufacturing processes, and structural configurations. GEC also made recommendations for testing composite coupons, details, assemblies, and blade sub-structures to be carried out in the Part II study (BSDS-II). The BSDS-II contract period began in May 2003, and testing was initiated in June 2004.

The current report summarizes the results from the BSDS-II test program. Composite materials evaluated include carbon fiber in both pre-impregnated and vacuum-assisted resin transfer molding (VARTM) forms. Initial thin-coupon static testing included a wide range of parameters, including variation in manufacturer, fiber tow size, fabric architecture, and resin type. A smaller set of these materials and process types was also evaluated in thin-coupon fatigue testing, and in ply-drop and ply-transition panels. The majority of materials used epoxy resin, with vinyl ester (VE) resin also used for selected cases. Late in the project, testing of unidirectional fiberglass was added to provide an updated baseline against which to evaluate the carbon material performance.

Numerous unidirectional carbon fabrics were considered for evaluation with VARTM infusion. All but one fabric style considered suffered either from poor infusibility or waviness of fibers combined with poor compaction. The exception was a triaxial carbon-fiberglass fabric produced by SAERTEX. This fabric became the primary choice for infused articles throughout the test program. The generally positive results obtained in this program for the SAERTEX material have led to its being used in innovative prototype blades of 9-m and 30-m length, as well as other non-wind related structures.

Testing of composite articles was performed at three laboratories: Integrated Technologies (Intec) in Everett, Washington; Montana State University (MSU) in Bozeman; and Wichita State University (WSU).

Results and observations from the testing are summarized in the following sections.

1.1 Thin Coupon Static

1.1.1 Carbon Fiber

Thin-coupon testing of prepreg materials showed little variation in static strength with manufacturer or tow size. Average values for compressive static strain were typically in the range of 1.0%-1.1%.

The SAERTEX carbon-fiberglass triaxial fabric with epoxy infusion achieved static strain values similar to prepreg materials. However, because of the inclusion of the ±45° glass, the modulus and stress at failure are both lower than for the unidirectional carbon prepreg. These results show that the carbon fibers in the infused laminate are reaching performance levels comparable to that of a unidirectional prepreg.

With VE infusion, the SAERTEX triaxial materials achieved slightly higher compressive static strength than that of the epoxy-infused articles. However, the compressive modulus measured by Intec for the VE infused panels was 13% higher than measured for the epoxy material. As a result, the calculated static compressive strain was 8% lower for the VE coupons.

Because the fabric was the same in both cases, and the measured panel thickness and fiber volume fractions were nearly identical, the large difference in modulus would not be expected. In general, the stress measurement which is based on applied load is more reliable than the compressive modulus measurement, which is based on a strain gage on a small specimen. Nonetheless, to maintain consistency in the presentation and analysis of data, GEC has used measured compressive modulus to calculate compressive strain.

1.1.2 Fiberglass

Static testing was performed for the E-LT-5500 fiberglass fabric, infused with both epoxy and VE resin. In general, the fiberglass material showed good performance in static strength for both epoxy and VE. Average tensile strain approached 2.3% for both resin systems, with very low scatter in the measurements. Average compressive strains were only slightly lower at approximately 2.2%.

1.2 Thin-Coupon Fatigue

1.2.1 Carbon Fiber

Two types of carbon fiber were tested in a prepreg form: Toray T600 (24k) and Zoltek Panex 35. Each of these fibers was impregnated by SP Systems using their WE90-1 resin and PMP process. Results for a third type of prepreg carbon fiber material were provided by MSU for comparative purposes, fabricated from Grafil 34-600 fibers (48k) and Newport NB307 resin. For all three prepreg materials, thin-coupon fatigue testing was performed at R = 0.1, 10 and -1. Overall, the three prepreg carbon materials showed similar fatigue performance. No consistent trend was seen concerning tow size for the fibers evaluated.

Epoxy-infused (SAERTEX triax) fabric preformed fairly well in fatigue relative to the prepreg materials. At R = 0.1, the infused material strains were modestly higher than the Toray/SP prepreg. For R = -1, the infused material strains were slightly higher at low cycles, and converged with the prepreg strains at high cycles. A different trend was seen for R = 10 fatigue. At the single-cycle end of the ε-N curve, the infused triax panel strains are about 10% higher than the prepreg, but at 1E+6 cycles, the triax strains fall below the prepreg by 20%.

For the infused carbon panels in tension (R = 0.1), the fatigue performance of VE was generally lower than epoxy. The single-cycle stress for the infused VE material was slightly higher than for the epoxy, but was about 25% lower at a million cycles.

Significantly different trends are seen in the fatigue stress data for compression and reversed loading, with a much smaller difference between the VE and epoxy results. In R = 10 loading, the VE stress levels were consistently higher than the epoxy, with a differential of about 5% at low cycles, growing to more than 10% at high cycles. Fatigue data for R = -1 are relatively sparse and show only modest difference in measured stress between epoxy and VE. The VE curve is steeper than that for epoxy, partly due to higher values of single-cycle stress. As noted above, applying the measured compressive modulus values to these curves would result in a downward shift of the calculated VE strains relative to the epoxy. Because the static testing at Intec had measured higher modulus values for the infused VE panels than for the epoxy, a strain-based compassion tends to shift all the VE curves downward relative to the epoxy data.

1.2.2 Fiberglass

Fatigue testing was also performed for the E-LT-5500 fiberglass fabric, infused with both epoxy and VE resin. In both tension and compression, the single-cycle strain values showed modest variation between the epoxy and VE resins.

Several trends were noted for the tension (R = 0.1) ε-N curve. For both the epoxy and VE resins, the intersect of the curves at zero cycles is substantially higher than the measured single-cycle strain. At higher cycles, the VE tension fatigue strength falls consistently below that of the epoxy. For the VE data, the tensile strain at 1E+6 cycles (based on the ε-N curve) was not particularly good, with a value of about 0.6%.

Significantly different trends are seen for the compressive fatigue data (R = 10). Most notable is that the VE data are consistently above that of the epoxy. The curves are also flatter, and the predicted strain levels at 1E+6 cycles are meaningfully higher than those seen for the R = 0.1 data. However a careful comparison the tension and compression data indicates that this may be an artifact of the sparseness of the R = 10 data sets combined with the relatively flat slope for the curve fits.

1.3 Thick Coupon

Obtaining reliable results for thick coupons proved difficult. Using the ASTM D6641 coupon geometry and combined loading in compression (CLC) fixture, seven 12.5-mm wide coupons and four 25-mm wide coupons were successfully tested at the Wichita State University (WSU). Subsequent attempts to conduct fatigue testing with the D6641 coupon caused damage to WSU's CLC fixture and as a result thick-coupon testing was terminated.

1.4 Carbon Ply Drop

In general, asymmetries in the ply drop and ply transition panels created challenges for obtaining reliable results in compression testing. Therefore, the majority of fatigue testing was performed for R = 0.1. Similar trends could be expected for R = 10, and R = -1, with an overall reduction in the fatigue performance expected.

For all fabric and resin styles, a ply drop with a straight edge resulted in low fatigue performance. For prepreg laminate, the introduction of a pinked ply-drop edge nearly doubled the strain level for delamination at 1E+6 cycles. With the infused fabrics, the pinked edge showed far less benefit, with a strain improvement at 1E+6 cycles of only about 25%.

The relatively low fatigue performance for the infused ply drops with pinking may be partly due to the geometry of the ply drops and panels. Visual inspection after resin burn-off showed that the shape of the pinked fabric was significantly better for the prepreg than for the infused articles. MSU also noted the contribution of through-the-thickness asymmetry to the failure mode of the infused ply-drop articles.

1.5 Carbon-Fiberglass Ply Transition

It is expected that carbon-to-fiberglass ply transitions will be of high interest as blade designers seek to optimize the use of carbon fiber in wind turbine blades. Panels were fabricated for axial testing in an attempt to quantify the performance of such a feature.

Ply-transition panels were fabricated in two basic configurations. One was designated mostly carbon, in which the article might represent the first carbon ply being transitioned to fiberglass in a carbon spar cap. The other was designated mostly fiberglass, and would represent the last carbon ply being transitioned. These two arrangements were considered as the bounding cases for the carbon-to-glass transition of a structural spar. Both of these configurations were fabricated in prepreg and infused articles. For the prepreg transition panels manufactured at MSU, two layup schedules were used, transitioning either one or two plies.

Initial ply-transition panels were infused by TPI Composites using the SAERTEX carbon-glass triaxial fabric. Testing at MSU showed unexpectedly poor performance in tensile strength, with delaminations initiating at relatively low strain values. The early delamination was attributed primarily to asymmetry in the thickness taper and the placement of fiberglass doublers at the outer-most location in the stack of unidirectional plies.

Based on the lessons learned from the initial infused articles, the transition panels were redesigned and fabricated at MSU using Grafil/Newport prepreg material. In an attempt to delay the onset of delamination, the fiberglass doublers were moved to the interior of the unidirectional fabric stack.

R = 0.1 testing of the redesigned prepreg panels has been completed at MSU. The data show a significant reduction in fatigue performance in going from one to two ply transitions (mostly glass data). However, the tensile strain values for delamination at 1E+6 cycles is close to 0.5%, which compares somewhat favorably with results for the ply-drop coupons.

As of this report date, testing at MSU is ongoing for prepreg transition panels in compression, and for second-iteration epoxy-infused ply-transition panels at R = 0.1, 10, and -1. Results from these tests will be reported by MSU as part of the ongoing development of the DOE/MSU Database.

1.6 Summary

A range of carbon fiber styles and tow sizes was tested in prepreg form, and were generally found to have little variation in performance.

Numerous unidirectional carbon fabrics were considered for evaluation with VARTM infusion. All but one fabric style suffered either from poor infusibility or waviness of fibers combined with poor compaction. The exception was a triaxial carbon-fiberglass fabric produced by SAERTEX. This fabric became the primary choice for infused articles throughout the test program. The generally positive results obtained in this program for the SAERTEX material have led to its being used in innovative prototype blades of 9-m and 30-m length.

Infused articles were tested with both epoxy and VE resin systems. Comparisons between prepreg and infused epoxy, and between infused epoxy and VE, were somewhat complex. In some cases, the performance variations were minimal and in other instances they were quite significant. For complex articles (ply drops and ply transitions), the comparison between prepreg and VARTM articles was complicated by the relative lack of symmetry in the infused articles.

The testing performed in this program has substantially added to the public-domain data for carbon fiber materials suitable for use in wind turbine blades. While numerous challenges were encountered during the course of this project, the results are nonetheless expected to be of value to the wind turbine blade design community.

Section 2 - Introduction

2.1 Background

In recent years both the size of wind turbine blades and the volume of production have been steadily increasing. Rotors over 90 m in diameter are on current commercial machines, and several turbine developers have prototypes in the 100-m to 120-m diameter range. It is estimated that over 160 million kilograms of finished fiberglass laminate were used for the production of wind turbine blades in 2006, and that worldwide production volume will increase for the next several years (calculations based on available weight data for commercial blades and the global wind energy market predictions of BTM Consult's *World Market Update 2005* [1]).

These growth trends have been accompanied by extensive research and development efforts in the blade manufacturing industry. In addition, government-funded programs in both Europe [2-6] and the United States [7-9] have been investigating alternative blade design and material technologies. Technical challenges include restraining weight growth, enabling larger rotors by increased stiffness, improving power performance, mitigating loads, facilitating transportation, and designing for fatigue cycles on the order of 10^7.

2.2 Project Overview

This project was initiated under the U.S. Department of Energy's Wind Partnerships for Advanced Component Technologies (WindPACT) program, which was intended to explore technologies available for improving wind turbine reliability and decreasing the cost of energy. Under the Sandia-sponsored Blade System Design Studies (BSDS), alternative composite materials, manufacturing processes, and structural designs were evaluated for potential benefits for MW-scale blades [7, 8]. The BSDS has two parts. Part I was analytical and included trade-off studies, selection of the most promising technologies, identification of technical issues for alternative materials and manufacturing approaches, and development of recommendations for materials testing. Part II, funded under the DOE's Low Wind Speed Turbine (LWST) program, involves testing of coupons and blade sub-structures with the objectives of evaluating composite materials and resolving technical issues identified in the Part I study. The content in this paper focuses on composites testing performed under the Part II study.

2.2.1 Major Trends and Results from BSDS-I

This section reviews some of the major conclusions and technical issues identified during the Part I study, which guided the development of the test matrix for the Part II study. These issues are discussed in greater detail in the *Blade Systems Design Studies Volume II: Preliminary Blade Designs and Recommended Test Matrix* report [8].

No absolute barriers were identified for the cost-effective scaling of the current commercial blade designs and manufacturing methods over the size range of 80-m to 120-m rotor diameters. The most substantial constraint is transportation cost which rises sharply for lengths above 46 m (150 ft) and may become prohibitive for long haul of blades in excess of 61 m (200 ft). Gravity loading is a design consideration but not an absolute constraint to scaling-up of current conventional materials and blade designs over the size range considered. Another issue for turbine design is the use of larger rotors at a given turbine system rating. As specific rating is decreased (i.e., blade lengths increase at a given rating), blade stiffness and the associated tip deflections become critical for cost-effective blade design.

Historically, wind turbine blades have been made predominantly from fiberglass materials. In the Part I study, trade-off studies were performed to evaluate the potential for cost-effective use of carbon fiber. Figure 2-1 illustrates the basic structural layout considered in that work, with carbon forming the primary load-bearing spars, and the blade skins and shear-webs being panels of a sandwich-style fiberglass construction. For this configuration, the spar caps are primarily unidirectional carbon fibers, and the skins are typically biaxial or triaxial fiberglass.

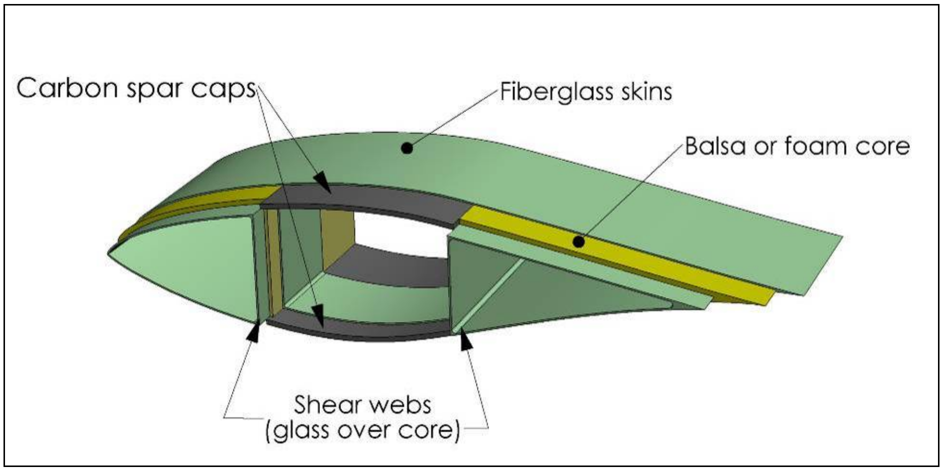

Figure 2-1. Architecture of BSDS Baseline Structural Model

During the time of the Part I study, industrial-style carbon fibers were available at historically low prices, and trade-off studies predicted that bulk replacement of fiberglass spar laminate with carbon fibers could result in improved blade structural properties at a reduced cost relative to an all-fiberglass blade. However, in recent years, demand and cost for carbon fiber have both increased sharply. As a result, bulk replacement of a fiberglass spar in an otherwise conventional blade design has become less economically viable. To justify the added material expense, blade designers are motivated to use the properties of carbon fibers to achieve system-level benefits.

For example, carbon fibers can be used to enable a slender blade profile, which will reduce the loading on the blades, towers, and other major structural components. Another concept under development is to skew the carbon fibers in a way that achieves load mitigation through aeroelastic response (e.g., bend-twist coupling). In either of these cases, some added cost in the blades may be offset by savings due to reduced loads on other major components. Partial-span carbon spars are another option for large blade designs. The motivation is that the greatest benefits from carbon fiber (in terms of decreased deflections and gravity-induced bending loads) are realized in the outer portion of the blade span. However, this design approach necessitates a transition from fiberglass to carbon spar caps (see Section 5.4), which presents added challenges in design, manufacturing, and cost-effectiveness.

2.2.2 Objectives for BSDS-II

The primary objectives for the Part II study are to perform coupon and sub-structure testing to:

- evaluate material and process combinations with promise for application to MW-scale blades,
- develop data required to determine performance/cost, and
- make the results available to U.S. wind industry.

In an attempt to maximize the relevance of this project, GEC has sought to work collaboratively with existing companies in the composite materials and wind turbine industries, including both suppliers and potential end-users. Efforts have also been made to ensure that the program is complementary with the ongoing DOE/MSU Database testing at Montana State University [10].

2.2.3 Technical Issues for Use of Carbon Fiber Materials

2.2.3.1 Tow Size

Carbon fiber is typically characterized by tow size, which indicates the number, in thousands, of fiber filaments per strand of material. Of interest for blade applications are lower cost industrial grades comprising either moderate (24k) or large (48k+) tow carbon fibers. These industrial-tow fibers tend to have reduced strength properties and reduced product uniformity (fiber straightness and purity) compared with aerospace-grade materials.

2.2.3.2 Production Processes

Although several manufacturers are still using open-mold, wet layup processes, increasingly stringent environmental restrictions have resulted in a move toward processes with lower emissions. Currently, two methods have emerged as the leading replacements for traditional methods: preimpregnated (prepreg) materials and resin infusion. Vacuum assisted resin transfer molding (VARTM) is the most common resin infusion method. Both VARTM and prepreg materials have particular design challenges for manufacturing the relatively thick laminate typical of large wind turbine blades. For VARTM processes, the permeability of the dry preform determines the rate of resin penetration through the material thickness. For prepreg material, sufficient bleeding is required to avoid resin-rich areas and eliminate voids from trapped gasses.

Although prepreg materials have historically been more expensive and require higher cure temperatures than liquid epoxy resin systems, the majority of commercial wind turbine blades that incorporate carbon fiber do so with prepreg materials. Conversely, most turbine blade manufacturers still produce primarily fiberglass blades using a wet process, either VARTM or an open mold layup and impregnation. Dry layup of preforms and subsequent infusion therefore remains a process of high interest for the wind industry.

2.2.3.3 Fabric Architecture for VARTM Laminate

Obtaining good structural performance with a VARTM process presents fundamental engineering challenges. Features in a dry fabric that promote infusion (e.g., stitching, gaps) also tend to induce fiber waviness and/or resin-rich areas. This can lead to strength reductions in both static compression and fatigue. Because of the high stiffness of carbon fibers, detrimental effects due to alignment/resin concentration are greater than for fiberglass laminates. GEC has evaluated numerous fabric styles during this project in an attempt to identify architectures that are favorable both for infusibility and structural performance. This will be discussed in greater detail in the following sections.

2.2.3.4 Thick Laminate

Thick laminate tests were expected to be of value to evaluate several technical issues. The first is simply thickness scaling of basic carbon/hybrid spar cap laminate. Typically, thicker laminate will include a greater distribution of naturally occurring material defects than the smaller coupons, and also a greater opportunity for fabrication-related irregularities. Given the relatively large strand size of commercial carbon fibers and the heavy-weight fabrics in use for large blades, some investigation of basic thickness effects is planned.

2.2.3.5 Ply Drops and Transitions

It is expected that ply drops in load-bearing carbon spars will cause a greater decrease in fatigue strength than in an equivalent fiberglass structure. This is due to the carbon fibers being more highly loaded than the fiberglass and as a consequence, shearing a higher load per unit area into the resin-rich region at the ply termination. An additional effect may be due to any waviness or jogs that are introduced in the remaining carbon plies as a result of the ply drop. Ply thickness is another important parameter for ply drops. The technical issue at hand is the trade-off between the increase in processing/handling efficiency of blade construction and the decrease in fatigue performance at ply drops which would be expected for the thicker carbon plies.

In general, carbon-to-fiberglass ply transitions have all of the technical considerations of carbon ply drops (i.e., load transfer though resin-rich areas, sensitivity to carbon layer straightness, and ply thickness). However, ply transitions also add the complication of mismatch between the carbon and fiberglass ply stiffness and strain-to-failure.

2.2.4 Test Matrix

The Part II study test matrix has undergone several modifications over the course of the project. Reference 8 contains the original test matrix, which is also reproduced in Appendix A. Table 2-1 summarizes the August 2004 revision to the planned testing. Changes relative to the original test matrix are an increase in scope of thin-coupon static and fatigue testing, and the elimination of a specialty cylinder, with combined axial and torque loading intended to evaluate fabrics with biased fibers (e.g., for twist-coupled blades). This latter test was eliminated due to greater-than-anticipated difficulties in early test efforts and the expected difficulties with the specialty cylinder test.

Table 2-1. Overview of BSDS-II Test Matrix (Revision August 2004)

Technical Issue	Type of Testing Planned
Basic performance of candidate materials	• Thin coupon • Thick coupon • Static and fatigue
Ply drops and carbon-fiberglass ply transitions	• Thin coupon (single ply drop/transition) • Thick coupon (multiple ply drops/transitions) • Variations on ply thickness
Performance of complete spar design, with ply drops and/or transitions	• 4-point beam bending

The original intent of this project was to perform the basic test types listed in Table 2-1 for both prepreg and VARTM processes, with carbon fibers in both the moderate and large tow-size categories. However, due to combined considerations of cost, schedule, and greater-than-anticipated difficulties with the testing, the following changes were made to the August 2004 test matrix:

- The number of thin-coupon tests (both static and fatigue) was increased relative to the initial test plans.
- A small number of thick-coupon static tests were performed. Fatigue testing of thick coupons was eliminated.
- 4-point beam tests were not conducted.
- While the baseline resin type for this program was epoxy, a limited number of test articles were evaluated using a vinyl ester (VE) resin system.
- Late in the program, a decision was made to also evaluate thin fiberglass coupons in both static and fatigue testing.

2.2.5 Organization and Scope of Report

This report summarizes the testing performed under the Part II study. As noted above, many difficulties were encountered in obtaining reliable results for the planned testing. While it is worthwhile to retain the knowledge of what worked poorly, the reliable data are of primary interest to anyone evaluating carbon for potential application in a wind turbine blade. Therefore, this report is organized to first emphasize the highest confidence results and data sets, with supporting details and discussion of unsatisfactory testing appearing as appendices.

Section 3 - Test Methods

3.1 Test Laboratories and Environment

All tests were conducted at indoor ambient conditions at the test facilities listed in Table 3-1. The following sections list the methods/standards used for each type of test. Additional details on the coupon geometry and loading fixtures is available in Appendix B.

Table 3-1. Test Facilities Sub-Contracted by GEC

Lab	Location	Tests Conducted
Integrated Technologies, Inc. (Intec)	Everett, Washington	Physicals, static and fatigue strength, thin and thick coupon
Montana State University (MSU)	Bozeman, Montana	Fatigue, thin coupon, ply-transition articles
Wichita State University (WSU)	Wichita, Kansas	Static, fatigue, thick coupon

3.2 Physical Properties

Standard testing for physical properties included resin digestion per ASTM D3171-99/D2734-99. Using nominal (specified) values for density of fibers and resins, the results from the resin digestion tests were analyzed to determine the laminate density as well as the volume fractions for fiber, resin, and voids. Glass transition temperature was determined from a temperature-deflection curve using the method of intersecting tangents.

In some of the earliest test specimens, an unexpected level of porosity and small delaminations were noted between coupon plies. As a result, the use of C-Scans was added as an additional quality-control measure for incoming test panels. Figure 3-1 and Figure 3-2 show examples from the C-Scan inspections. The darker colors (purple and black) indicate relatively lower void content, whereas orange and red are on the higher void side of the spectrum. Qualitatively, Figure 3-1 shows uniformly low void content. Conversely, Figure 3-2 indicates a higher overall level of voids, with more spatial variation over the panel.

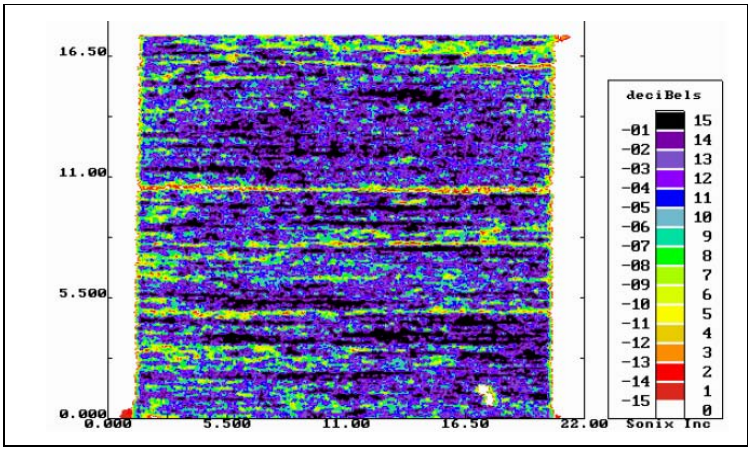

Figure 3-1. Example of Panel C-Scan (Uniformly Low-Void)

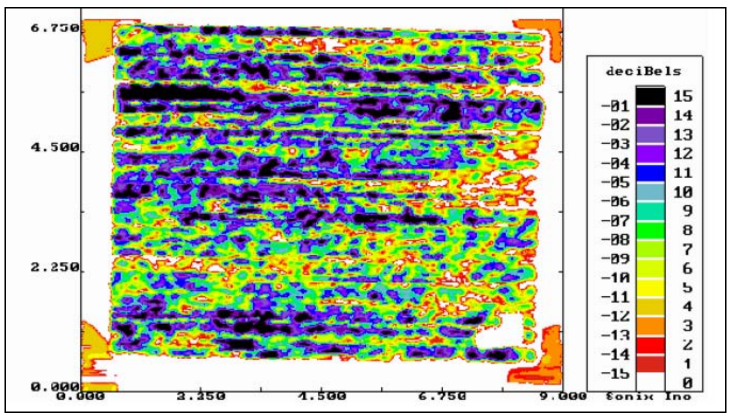

Figure 3-2. Example of Panel C-Scan (Higher Void with Non-Uniformity)

3.3 Thin-Coupon Static

Table 3-2 lists the standards used for the majority of the thin-coupon static tests. Notable deviations from the typical standards are as follows:

- Initial static compression tests at Intec used ASTM D3410, with varying standard and non-standard gage section lengths. Due to difficulty obtaining consistent test results, GEC requested that Intec use the ASTM D695 methods for compressive tests.
- For selected cases, ASTM D3410 was then used to obtain the single-cycle data points for fatigue curves that involve compression. The single-cycle data are differentiated from static tests in that a higher rate of loading has been used in the single-cycle tests to match the rate use in fatigue testing. Because of load-rate effects, the rapidly loaded single-cycle data will typically indicate higher strength than the static tests.

Table 3-2. Test Standards Used for Thin-Coupon Static Tests

Description	Standard Used	Coupon Configuration
Tension Strength and Modulus	ASTM D3039/D3039M – 00	230 mm x 25 mm, tabbed
Compression Strength	ASTM D695 – 02a (modified)	84 mm x 12.7 mm, tabbed
Compression Modulus	ASTM D695 – 02a (modified)	84 mm x 12.7 mm, untabbed

3.4 Thin-Coupon Fatigue

Composite material fatigue test standards are currently under development in the United States. In the absence of such standards, the testing was primarily conducted using methods developed and/or recommended by MSU. The D3410 coupon geometry was typically used for compression-compression (R = 10) and tension-compression (R = -1), whereas the ASTM D3039 was used for tension-tension (R = 0.1). Loading rates were determined as appropriate, within the capacity of the load frame and hydraulics and avoiding premature failure due to heat rise. Details on the loading rates (frequencies) are given in Appendix E.

3.5 Thick-Coupon Compression

Thick-coupon testing proved difficult. Two initial tests were performed at Intec using a relatively long dog-bone style geometry, with buckling restraints in the gage section. The first resulted in a grip failure, and in the second test, the buckling restraints proved unstable. The dog-bone specimen geometry was not pursued further in this project.

Subsequent thick-coupon testing was conducted at WSU, with a specimen geometry that utilizes an ASTM D6641 combined loading compression (CLC) test fixture. The coupon geometry and test fixture are shown in Appendix B. As will be discussed below, a limited number of static tests were succesfully completed with this method before thick-coupon testing was terminated.

3.6 Measurement and Reporting of Elastic Modulus/Strain

The measurement of elastic modulus and reporting of both modulus and strain present several alternative and technical considerations. In most of this testing, tensile modulus is measured via extensometers on specimens that have relatively long gage-section lengths. Conversely, compressive modulus is typically measured with strain gages on very short gage sections. This introduces differences between the tensile and compressive modulus tests, both in methodology, as well as the magnitude of the dimension being measured.

Even in the linear-elastic range, it is not uncommon in fiber-reinforced plastic materials to measure a different modulus for tension and compression with the compressive modulus tending to have the lower value. The term chord modulus is used to indicate a value calculated from a specific portion of the stress-strain curve. For test data reported herein, measurements of chord modulus have been made in the range of 1000 to 3000 micro-strain ($\mu\varepsilon$). In the current test program, deviations between measured tensile and compressive chord modulus have varied from negligible to as high as 17%. Although most finite element analysis (FEA) codes can accommodate non-linearities in modulus values, it is typical for designers to use a single value (per coordinate axis) for elastic modulus. Therefore care must be taken to maintain consistency in both the reporting and use of modulus and strain data.

To add further complication, the stress-strain curves for test articles do not remain linear. In general, composite materials tend to exhibit a stiffening of the fibers under tensile loading prior to failure, and a softening under compressive loading. The latter effect is illustrated in the measured stress-strain data of Figure 3-3. The compressive stress and strain at failure were measured to be 830 MPa and 1.3%, respectively. The secant modulus, shown in red (triangle), is a linear fit between zero and maximum strain. The secant modulus gives the correct strain at maximum stress, but does not accurately reflect the stress-strain relationship in the midrange of strain values.

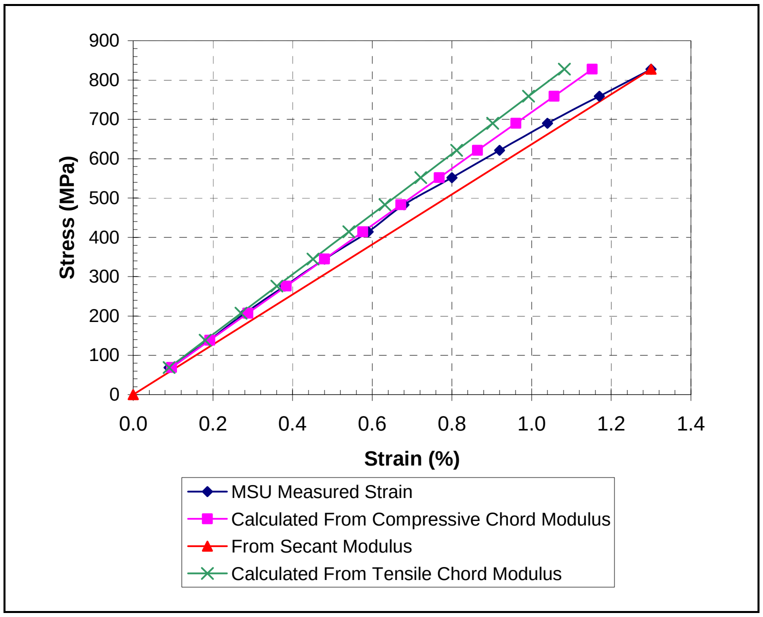

Figure 3-3. Data Set Illustrating Modulus Variations

Figure 3-3 also shows calculated stress-strain curves based on the measured compressive and tensile chord modulus. The variation in slopes and calculated maximum strains for these curves reflects the differential in measured tensile and compressive modulus, which for these coupons was about 6.5%.

For work conducted under this project, the methodology used for strain values reported to GEC has varied somewhat from lab to lab and according to the testing conducted. In order to avoid inconsistencies in the final data sets, GEC has attempted to standardize the method for calculating strains in their project reporting. Wherever available, the measured tensile modulus was used to calculate tensile strain, and the measured compressive modulus was used to calculate compressive strains. Thus, if the reported strain values are used to guide design calculations, the different modulus values for tension and compression need to also be considered. However, since the underlying stress and modulus data are reported, designers can use these data sets in whatever way best suits their needs.

Section 4 - Test Article Fabrication

4.1 General

Four basic types of panels were tested in this program: thin, thick, ply-drop and carbon-to-fiberglass ply-transition. Each of these basic types can be further differentiated based on fabrication method: prepreg material or VARTM infusion.

For all the specimens, rectangular test panels were fabricated at room temperature under vacuum pressure. Typically, the laminate was vacuum-bagged with a caul plate on the lower side only, though some of the prepreg panels were formed using a glass plate on the top as well. The advantage of a two-sided caul is a smooth top surface that provides superior grip contact with the test coupon. Most panels included a biaxial fiberglass facing material at the outer surfaces. Inclusion of this feature was based on input from some test laboratories, namely that the facings improved the reliability of compression test results.

All of the VARTM panels were infused at TPI Composites, Inc. (Warren, Rhode Island), using their SCRIMP™ infusion process, using either epoxy or VE resin. A substantial number of prepreg panels were fabricated by SP Systems (Isle of Wight, UK). Later in the program, prepreg panels were formed at the MSU test laboratories.

4.2 Fabric Evaluation/Infusion Trials

As noted above, obtaining good structural performance with a VARTM process presents significant engineering challenges. As an example, Figure 4-1 shows how stitching can adversely affect the straightness of carbon fibers in a unidirectional fabric.

Figure 4-1. Stitched Fabric with Manufacturing-Induced Waviness

Initially, fabric evaluation and infusion trials were performed as part of work under a GEC Phase I Small Business Innovation Research (SBIR-I) Grant, which pre-dated the BSDS-II contract. GEC worked with numerous vendors in obtaining candidate carbon-fiber fabric styles for VARTM fabrication. In some cases, the fabric was eliminated from consideration by visual inspection of the fiber alignment (e.g., Figure 4-1). For other materials, resin infusion trials were performed by TPI. Fabrics that were disqualified by the infusion trials generally fell into one of two categories. The first is fabrics that had very good alignment, but were not permeable enough to allow resin penetration. The second is fabrics that infused well, but due to their looseness had poor compaction and low fiber-volume fraction (υ_f).

Figure 4-2 shows the most favorable fabric identified, a multi-layer, multi-axial warp-knit (MMWK) style produced by SAERTEX. GEC worked with the vendor and TPI to develop this architecture, originally under their SBIR-I Grant. The fabric is a triaxial construction [$-45°_{Glass}/0°_{Carbon}/+45°_{Glass}$], with areal weights of 150/670/150 gsm. The net fiber content is 75% carbon and 25% fiberglass by volume. Distinct features of this architecture and SAERTEX stitching style include those listed below:

- the outer layers are fiberglass, providing some protection of carbon fibers;
- the stitching pattern is such that it squeezes the glass strands, but runs parallel with and between strands of carbon fibers;
- the resulting fabric has good infusibility without introducing waviness in the carbon fibers; and
- the triaxial construction provides good stability for material handling.

Because of the relative success with this material, it became the primary fabric for VARTM test articles in this program. GEC continued to work with material vendors throughout the BSDS-II to identify other combinations of fiber style and fabric architecture with promise for good infusibility, compaction, and fiber straightness. However, no alternative carbon fabric was found to show sufficient performance for serious consideration.

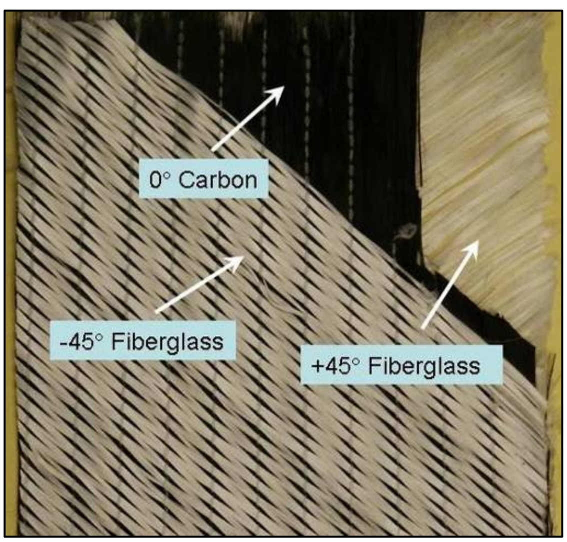

Figure 4-2. SAERTEX Triaxial Carbon-Fiberglass Fabric

4.3 Thin Panel

All thin panels were produced as described above. Details on fiber types, laminate schedules, and post-cure are given in Section 5.

4.4 Thick Panel

Due to difficulties encountered, only one thick-panel specimen was tested in this project. The panel was infused with epoxy resin using 12 plies of the SAERTEX carbon-glass triax shown in Figure 4-2. To minimize warpage, two plies of 400 gsm biaxial fiberglass were included on each surface. The finished panel dimensions were 1500 mm x 600 mm, with a nominal 12-mm thickness. There was no difficulty encountered with the infusion of the triaxial carbon-glass fabric at this thickness, and a C-scan did not indicate significant voids. Due to the thickness of the panel, however, the upper surface of the laminate had thickness variations that were noticeably greater than the thin panels, with overall panel variations of 1.3 mm from one edge to the other. Within each coupon, however, a maximum difference of 0.13 mm was measured.

A second thick panel was fabricated by MSU using unidirectional carbon prepreg. Specimens were machined by WSU for testing, but not tested.

4.5 Ply Drop Panels

Ply drop panels were fabricated in two styles: drops with straight edges and drops with pinked edges. Figure 4-3 shows a straight ply drop. Figure 4-4 illustrates the pinked ply drop, which is intended to reduce the stress concentration at the ply drop edge. In both figures the outer plies are not shown for clarity. An example detailed panel specification is given in Appendix C. Both the straight and pinked configurations were fabricated in prepreg and infused articles.

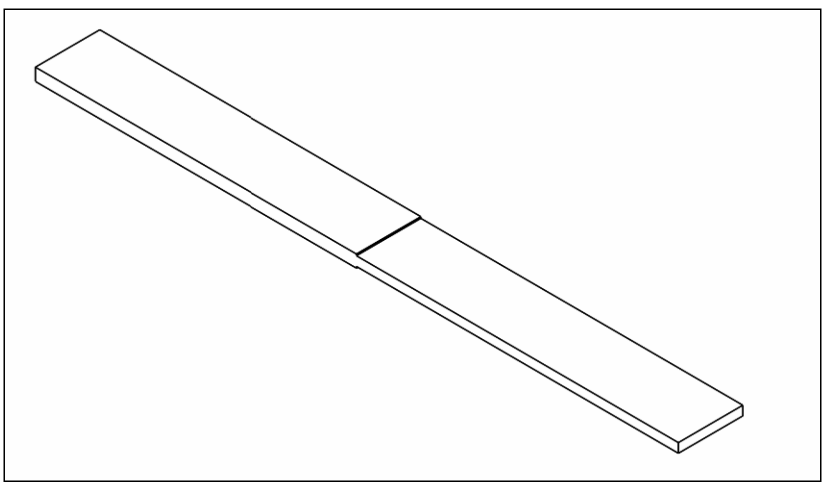

Figure 4-3. Straight Ply Drop (Outer Plies Not Shown for Clarity)

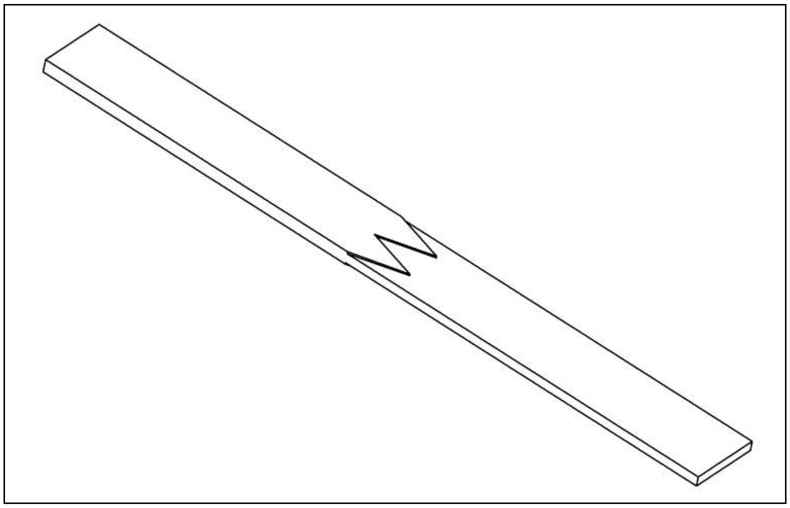

Figure 4-4. Pinked Ply Drop (Outer Plies Not Shown for Clarity)

4.6 Ply Transition Panel

Ply transition panels were designed in an attempt to mimic features that might occur in an actual blade design. Figure 4-5 illustrates the possible arrangement of such a transition. An example detailed panel specification is given in Appendix C. Ply transitions were fabricated in two basic configurations. One was designated mostly carbon, in which the article might represent the first carbon ply being transitioned to fiberglass in a carbon spar cap. The other was designated mostly fiberglass, and would represent the last carbon ply being transitioned. These two configurations were considered as the bounding cases for the carbon-to-glass transition of a structural spar. Both of these configurations were fabricated in prepreg and infused articles.

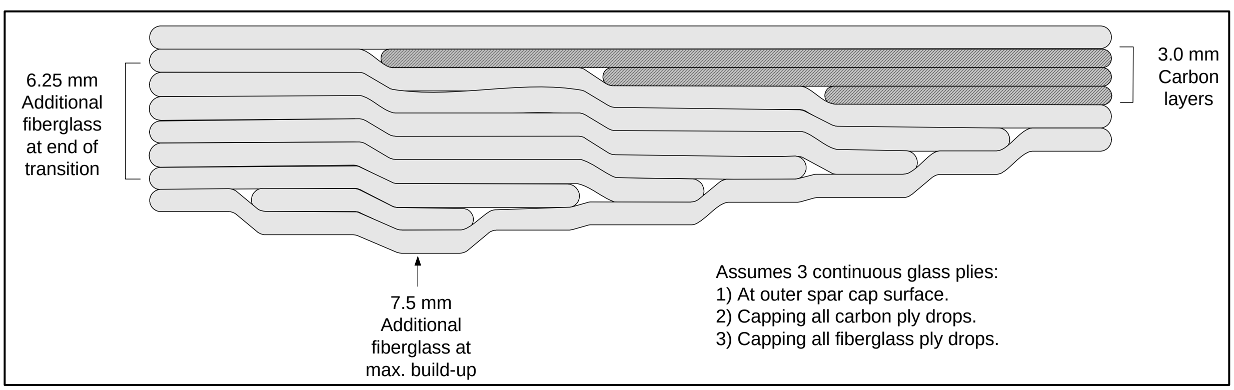

Figure 4-5. Conceptual Illustration of Carbon-to-Fiberglass Ply Transitions

Section 5 - Test Results

The following sections provide a summary of test results, along with a discussion of observed trends. The detailed tabular data are available in Appendix D (static testing at Intec) and Appendix E (fatigue testing at MSU).

5.1 Thin Coupon

5.1.1 Thin-Coupon Static Testing

Table 5-1 provides the description and test-article numbering for selected thin panels fabricated from prepreg materials. Although the carbon ply areal weights vary from 300 to 600 gsm, the number of unidirectional plies was also varied so that the total weight of carbon unidirectional material for all panels was 2400 to 2500 gsm. With the exception of panel I.D. 013X, all the articles listed include fiberglass facings.

Table 5-1. Numbering and Description for Prepreg Thin Panels

Panel I.D.	Carbon Ply Description: Manufacturer/ Type	Tow Size	Areal Weight (gsm)	Number of Plies	Glass Facing per Side (gsm)	Total Thickness (mm)	Matrix
013X	Tenax STS-24	24k	600	4	None	2.3	SP WE90-1
014X	Tenax STS-24	24k	600	4	400	2.9	SP WE90-1
016X	Toray T600	24k	500	5	400	2.7	SP WE90-1
211X	Toray T600*	24k	500	5	400	3.0	SP WE90-1 / PMP
018X	Zoltek Panex 35	50k	500	5	400	3.1	SP WE90-1
214X	Zoltek Panex 35*	50k	500	5	400	3.4	SP WE90-1 / PMP
031X	Grafil 34-600	48k	300	8	300	3.0	Newport NB307

*Note: SP Systems "proprietary manufacturing process" uses WE90-1 resin but not in conventional prepreg form.

Late in the program, an additional thin panel was fabricated from unidirectional prepreg fiberglass (Newport). However it was determined that the initial coupons were too thick to obtain satisfactory test results. No further effort was made to test prepreg fiberglass material.

Two of the panel styles using SP WE90-1 resin are shown with a PMP label. This is used to indicate that the panels were formed by SP using proprietary manufacturing process developed for the production of high-quality carbon-fiber preforms of thickness up to 50 mm, and used widely in the wind energy market. The PMP designation is not a formal trade name for this process, but has been used to differentiate between SP panels using conventional prepreg materials and panels with the same fiber and resin types, but formed using the alternative process. An example for the Toray T600 fibers is panel I.D. 016X (conventional prepreg) and I.D. 211X (PMP).

Table 5-2 summarizes the static test data for these articles. The measured fiber volume fractions are generally consistent with the panel thicknesses of Table 5-1. A subtle trend toward thicker panels and lower fiber volume fractions is seen for the large-tow (48k and 50k) as compared with the 24k moderate-tow fibers. For panels with glass facings, the tensile modulus showed high consistency between panels, varying from 103 to 113 GPa. Ultimate tensile strain values varied between 1.3% and 1.7%. For the majority of prepreg materials, calculated compressive strains were between 1.0% and 1.1%. A notable exception is the (high) value of 1.37% for the Grafil 34-600 tested at Intec. GEC suspects that this result may have been influenced by over-tightening of the bolts in the D695 fixture. Testing of this same panel at MSU yielded a substantially lower value of 1.11%, which is more consistent with test results from other materials.

Note that the static strength data in Table 5-2 and Table 5-5 include some data points with questionable failure modes such as tab failures. In such cases, GEC concluded that the results were generally reasonable, and may have given somewhat higher strength if failure modes related to tabs and/or grips could have been avoided. To avoid ambiguity on this issue, the complete data sets, including failure modes, have been included in Appendix D.

Table 5-2. Static Test Data for Prepreg Thin Panels

			Physical Properties			Tension						Compression						
						Mean Stress			Modulus		Strain	Mean Stress			Modulus			Strain
I.D.	Fiber	Lab	υ_f (%)	ρ (g/cm^3)	T_g (C)	#	σ_X (MPa)	COV (%)	E_X (GPa)	COV (%)	ε_x (%)	#	σ_X (MPa)	COV (%)	#	E_X (GPa)	COV (%)	ε_x (%)
013x	Tenax	Intec	56	1.52	104	5	1,956	3.1	132	2.4	1.48	6	1,186	3.9	5	113	4.9	1.05
014x	Tenax	Intec	55	1.59	95	6	1,655	4.9	108	2.9	1.53	6	1,129	8.4	5	101	3.7	1.11
016x	Toray	Intec	59	1.60	105	5	1,952	1.9	113	2.2	1.73	6	1,117	6.6	3	110	5.1	1.01
211x	Toray	Intec	54	1.59	104	-	-	-	-	-	-	5	1,243	1.7	5	110	3.3	1.13
018x	Zoltek	Intec	52	1.57	101	5	1,400	7.4	106	1.9	1.32	6	1,193	4.5	3	96	0.6	1.24
214x	Zoltek	Intec	48	1.54	108	-	-	-	-	-	-	5	1,037	2.5	5	104	0.6	1.00
031x	Grafil	Intec	52	1.58	134	6	1,570	1.6	103	3.7	1.52	6	1,310	6.1	5	96	1.9	1.37
031x	Grafil	MSU	53	-	-	3	1,496	6.5	97	1.5	1.55	2	1,070	11.0	-	96	-	1.11

Note: Intec compressive modulus measurement used for MSU test of panel 031x.

Table 5-3 provides the panel numbering and description of both thin and thick infused carbon articles. All of the infused articles use the SAERTEX carbon-fiberglass triaxial fabric style depicted in Figure 4-2. Table 5-4 gives the panel numbering and description for the thin infused fiberglass panels.

Table 5-3. Numbering and Description for VARTM-Infused Carbon Panels

Panel I.D.	Carbon Ply Description: Manufacturer/ Type	Tow Size	Areal Weight (gsm)	Number of Plys	Glass Facing per Side (gsm)	Total Thickness (mm)	Matrix
022X	Toray T600	24k	150/670/150 glass/carbon/glass	4	300	4.3	Epoxy, Jeffco 1401
026X	Toray T600	24k	150/670/150 glass/carbon/glass	4	300	4.2	Vinyl ester, Vipel F010
1211	Toray T600	24k	150/670/150 glass/carbon/glass	12	800	11.2	Epoxy, Huntsman LY 1564

Table 5-4. Numbering and Description for VARTM-Infused Fiberglass Panels

Panel I.D.	Glass Ply Description: Manufacturer/ Type	Glass Ply Description: Uni Glass Areal Weight (gsm)	Glass Ply Description: Number of Plys	Glass Facing per Side* (gsm)	Total Thickness (mm)	Matrix
020X	Vector Ply E-LT-5500-10	1865	2	580	4.5	Vinyl ester, Ashland Momentum 411-200
029X	Vector Ply E-LT-5500-10	1865	2	580	4.2	Epoxy, Huntsman LY 1564

* 3 plys total of DBM 1708, one each per face and one between uni glass plies.

5.1.1.1 Infused Fiberglass Static Results

Table 5-5 summarizes the static test results for the infused thin coupons, for both fiberglass and carbon fibers. The data in the tables indicate that for both fiber types, the compaction and fiber volume fractions show little difference between epoxy and VE resins. Note that the 53% υ_f measured for the fiberglass-epoxy panel (020X) is somewhat suspect, as that measurement had relatively large scatter and implied a void volume of -6.2%. Also notable in these data is a higher-than-expected glass transition temperature (T_g) for the fiberglass-VE panel. While these two physical property measurements are anomalous, the remainder of the strength and stiffness measurements for the fiberglass panels appear to be reliable.

In general, the E-LT-5500 fiberglass material showed good performance in static strength for both epoxy and VE resins. Average tensile strain approached 2.3% for both resin systems, with very low coefficients of variation (COV ≤ 2%). Average compressive strains were only slightly lower, and showed greater variability.(COV ≅ 6%-7%).

Table 5-5. Static Test Data for Infused Thin Panels

I.D.	Fiber	Resin	Physical Properties: υ_f (%)	Physical Properties: ρ (g/cm³)	Physical Properties: T_g (C)	Tension Mean Stress: #	Tension Mean Stress: σ_x (MPa)	Tension Mean Stress: COV (%)	Tension Modulus: E_x (GPa)	Tension Modulus: COV (%)	Tension Strain: ε_x (%)	Compression Mean Stress: #	Compression Mean Stress: σ_x (MPa)	Compression Mean Stress: COV (%)	Compression Modulus: #	Compression Modulus: E_x (GPa)	Compression Modulus: COV (%)	Compression Strain: ε_x (%)
022x	Toray	Epoxy	56	1.685	64	5	1,253	4.6	77.4	3.5	1.62	6	770	4.8	5	70.3	3.0	1.10
026x	Toray	VE	55	1.593	65	6	1,140	1.5	82.8	3.5	1.38	6	807	7.8	5	79.3	3.0	1.02
020x	E-Glass	Epoxy	53*	1.934	70	10	704	1.3	31.1	3.5	2.26	9	702	7.2	10	31.2	2.9	2.25
029x	E-Glass	VE	56	1.958	104	11	707	1.9	30.9	2.3	2.29	12	757	5.6	10	34.8	3.0	2.18

* 9.6% COV, 4 samples, -6.2% measured void volume.

5.1.1.2 Infused Carbon Static Results

Because the fabric styles and laminate schedules are identical between the epoxy and VE infused carbon panels, it is reasonable to expect the modulus values to also be in close agreement. However, Table 5-5 shows that the tensile and compressive modulus were 7% and 13% higher, respectively, for the carbon panels infused with VE rather than epoxy resin. The modulus variation results in some inconsistency between comparisons based on stress and strain. This is particularly evident for the compression case, where the mean compressive stress for the VE coupons was nearly 5% higher than the equivalent epoxy materials, but because of the differential in measured modulus the calculated VE compressive strain was 7.3% lower than for the epoxy. For tension, the VE material achieved a tensile stress of 9% lower than the epoxy.

Due to the differential in measured modulus, the calculated tensile strain for the VE was nearly 15% lower than the epoxy.

However, the most significant result is the high performance of the infused SAERTEX carbon-fiberglass fabric (ID 022x and 026x) with both epoxy and VE resins. Value for fiber volume fraction and compressive strain were both comparable to those seen for the prepreg materials in Table 5-2.

5.1.2 Thin-Coupon Fatigue Testing

5.1.2.1 General

Some of the following data were developed by MSU under the DOE/MSU Database program [10] and provided to GEC for comparative purposes. In the present report, strain values for most cases have been calculated based on measured compressive chord modulus. This approach is different from the typical methodology at MSU, and so the strain values plotted in the following figures may not agree with data presented by MSU. However, this approach has been used in the present work so that results from different materials can be compared on a self-consistent basis. For a limited number of cases, strain data have also been presented based on measured strain.

For all data, fatigue curves were developed of the forms:

$$\frac{\varepsilon}{\varepsilon_o} = A \cdot N^{-1/m}$$ **Equation 1**

Where:

ε_o ≡ single-cycle strain
A ≡ coefficient of the ε-N curve
N ≡ number of loading cycles
m ≡ inverse slope of the ε-N curve.

$$\frac{\sigma}{\sigma_o} = A \cdot N^{-1/m}$$ **Equation 2**

Where:

σ_o ≡ single-cycle stress

As long as stress and strain are related by a single constant (the elastic modulus), then the curve-fit parameters A and m will be the same for both the σ-N and ε-N curves. If strain data are based on measurements, rather than calculations from measured stress, then the curve fits for stress and strain may differ.

Fatigue testing is distinguished by the ratio of minimum divided by maximum stress, or R-value. Testing under the Part II study has so far included R = 0.1 (tension-tension), R = 10 (compression-compression), and R = -1 (tension-compression). All data herein have been analyzed and presented in terms of the absolute value of maximum stress in the fatigue loading cycle. In applying Equation 1 to fatigue curve fits, the compressive single-cycle value of ε_o was used for R = 10 and R = -1, and the tensile single-cycle ε_o was used for R = 0.1.

Summary results from the fatigue tests are given in graphical and tabular formats in the following sections. A detailed tabulation of the measured data and curve-fit calculations is provided in Appendix E.

5.1.2.2 Infused Fiberglass Fatigue Results

The testing of infused fiberglass in tension presented some challenges concerning analysis and presentation of the data. During the fatigue testing MSU observed that the ±45° plies tended to crack during the initial cycles, which reduced the stiffness and increased the material strain. This behavior was more significant for the fiberglass than for the carbon coupons for the following reasons: the infused fiberglass articles had a relatively large amount of ±45° content relative to the zero-degree plies, the stiffness contribution of the ±45° plies is significantly greater than for an equivalent coupon with carbon fiber zero-degree plies, and the strain levels for the fiberglass coupons are greater than is typical for carbon materials.

Because of these mechanisms, a significantly different ε-N curve would result from using a constant modulus to calculate strain as opposed to fitting the measured strains directly. For completeness, both analytical approaches are shown below. It should be noted that matrix cracking in the ±45° plies was not observed for compression, and the short gage sections used in the compression tests prevent accurate measurement of the strain. Therefore, the strain data for compression was calculated by MSU based on the measured (constant) value of the tensile modulus.

Figure 5-1 and Figure 5-2 show fatigue data for the E-LT-5500 fiberglass fabric, infused with both epoxy and VE resins. Strain values in these figures were calculated by GEC based on the MSU-measured stress levels combined with the average modulus measured by Intec in static testing. Curve-fit parameters (per Equations 1 and 2) are listed.

In both tension and compression, the single-cycle strain values (Table 5-6) showed only modest variation between the epoxy and VE resins. The single-cycle tensile strain was higher than the static value measured at Intec (Table 5-5), and the compressive single-cycle strains were lower than the corresponding static measurements. In the case of the tensile tests, both labs used ASTM D3039 coupons, but the single-cycle data of MSU had a higher loading rate. For the compressive tests, the Intec static measurements used ASTM D695, whereas the MSU fatigue tests used ASTM D3410, with varying standard and non-standard gage section lengths as needed to obtain satisfactory failure modes.

The ε-N curve of Figure 5-1 shows several trends. For both the epoxy and VE resins, the intersect of the curves at zero cycles is substantially higher than the measured single-cycle strain. This behavior is also indicated by the high values of the “A” curve-fit parameter seen for R = 0.1 in Table 5-6. At higher cycles, the VE tension fatigue strength falls consistently below that of the epoxy.

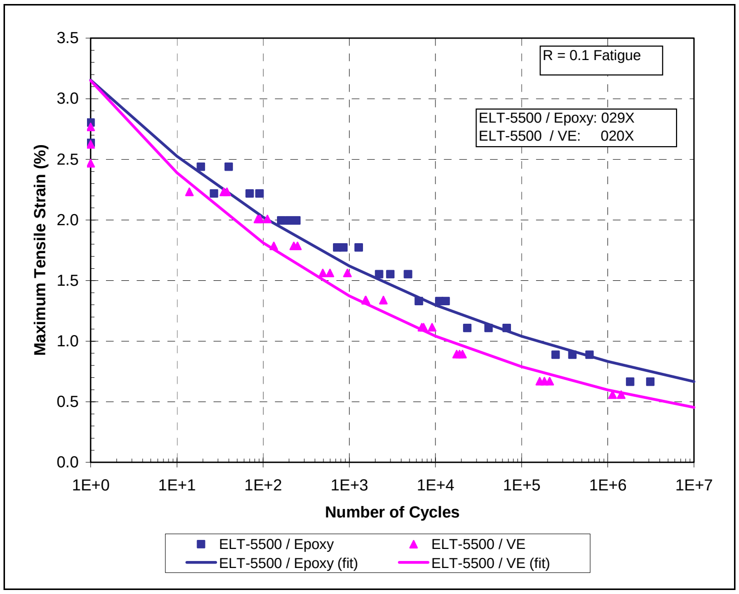

Figure 5-1. R = 0.1 Fatigue Data for Thin-Coupon Infused Fiberglass (Calculated Strains)

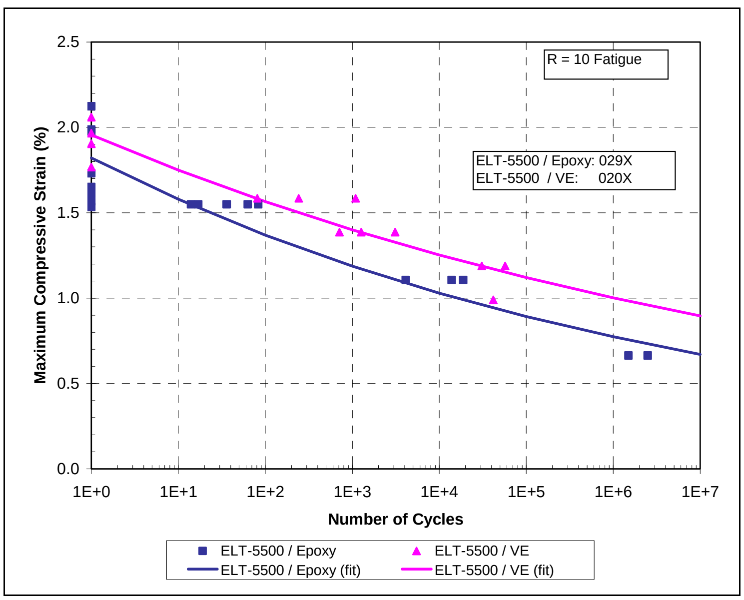

Figure 5-2. R = 10 Fatigue Data for Thin-Coupon Infused Fiberglass (Calculated Strains)

Table 5-6. Curve-Fit Parameters for Infused Fiberglass Thin Coupons (Calculated Strains)

	R = 0.1				R = 10			
Material	**σ_o (MPa)**	**ε_o (%)**	**m**	**A**	**σ_o (MPa)**	**ε_o (%)**	**m**	**A**
ELT-5500 / Epoxy	836.3	2.69	10.4	1.172	551.7	1.77	16.2	1.028
ELT-5500 / VE	808.9	2.62	8.4	1.202	653.8	1.88	20.7	1.041

Significantly different trends are seen for the compressive fatigue data of Figure 5-2. Most notable is that the VE data fall consistently above that of the epoxy. The curves are also flatter than those seen for the R = 0.1 data (higher values of slope parameter, “m”). Based on the curve fits, the predicted strain levels at 1E+6 cycles for R=10 are meaningfully higher than those indicated by the R = 0.1 curves. However a careful comparison of Figure 5-1 and Figure 5-2 indicates that this may partly be an artifact of the sparseness of the R = 10 data sets combined with the relatively flat slope for the curve fits.

Figure 5-3 shows the R = 0.1 ε-N curves based on measured rather than calculated strains. The overall trends are as seen in Figure 5-1, but with a general shift toward higher strain values. The corresponding curve-fit parameters are given in Table 5-7.

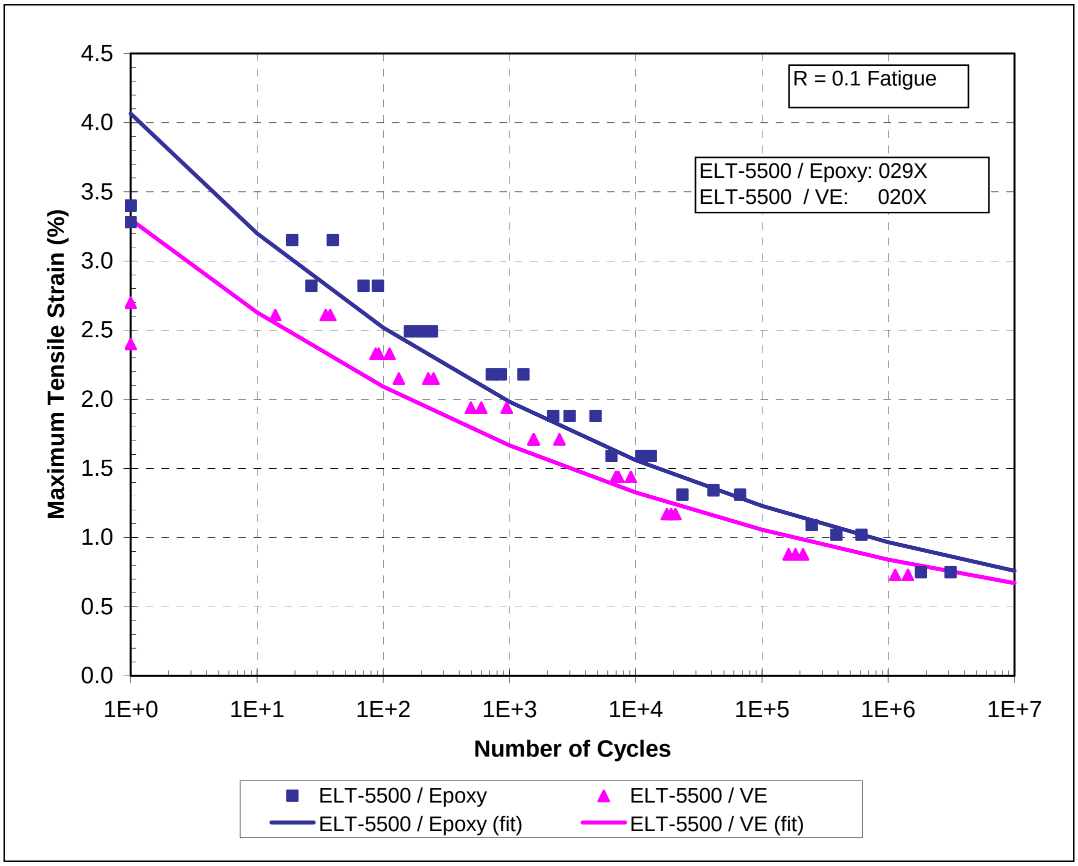

Figure 5-3. = 0.1 Fatigue Data for Thin-Coupon Infused Fiberglass (Measured Strains)

Table 5-7. Curve-Fit Parameters for Infused Fiberglass Thin Coupons (Measured Strains)

	R = 0.1		
Material	**ε_o (%)**	**m**	**A**
ELT-5500 / Epoxy	3.36	9.6	1.210
ELT-5500 / VE	2.50	10.1	1.320

5.1.2.3 Prepreg Carbon Fatigue Results

Figure 5-4 through Figure 5-6 show fatigue data for three styles of carbon prepreg material. Curve-fit parameters are listed in Table 5-8. The data for the Grafil/Newport material were developed by MSU under the DOE/MSU Database program. Data for Toray and Zoltek fibers (SP WE90-1 resin with PMP) were from testing conducted at MSU under the BSDS-II study.

The data of Figure 5-4 show that for R = 0.1 fatigue the Grafil and Toray fiber ε-N curves were consistently above the corresponding Zoltek data. At high cycles, the Grafil fibers showed the best performance, with the Toray curve crossing at around 30 cycles due to slightly higher values for single-cycles strain. All three curves for R = 0.1 fatigue were very flat, with slope parameter (m values) ranging from about 31 to 48.

The trend for compression fatigue was somewhat different. Figure 5-5 shows that for R = 10 the two moderate-tow fibers had very similar ε-N curves for R = 10 fatigue, with the Toray data being only slightly favored. The large-tow (Zoltek) data showed higher values for single-cycle compression, and a somewhat steeper slope throughout the curve. Nonetheless, all three curves for R = 10 fatigue were again flat. The slope parameter values were m ≈ 46 for the Grafil and Toray fibers, and m ≈ 28 for the Zoltek fiber.

For fully reversed loading, the Toray and Zoltek curves were quite similar to one another. By comparison, the Grafil curve was flatter, with reduced magnitude of single-cycle strain, and higher strain values at large cycles (Figure 5-6).

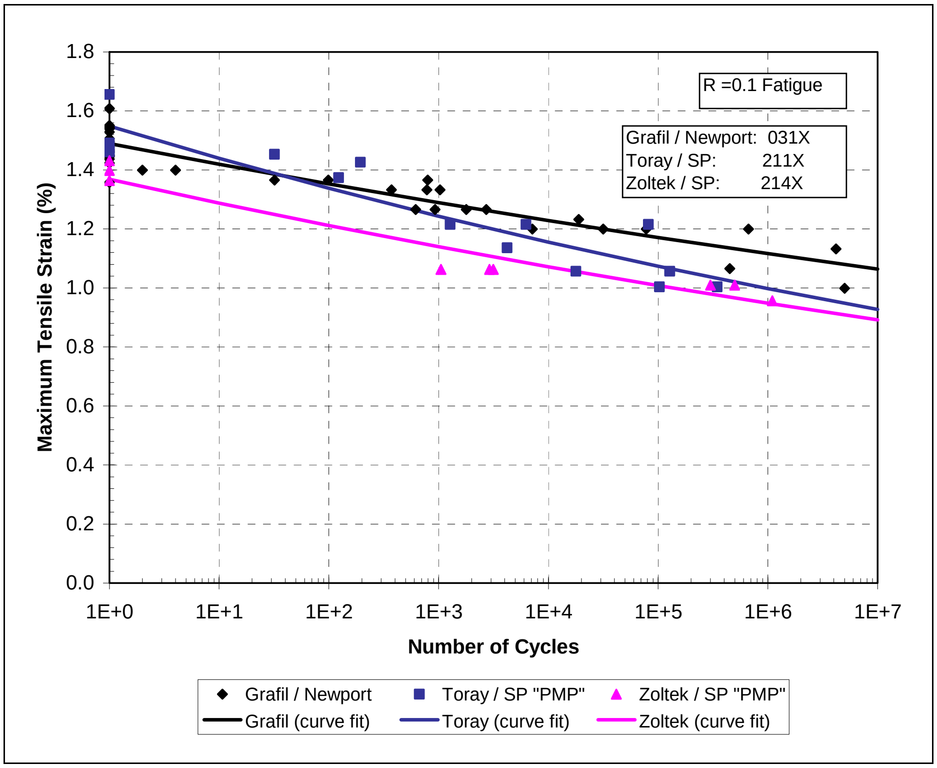

Figure 5-4. R = 0.1 Fatigue Data for Thin-Coupon Prepreg Panels

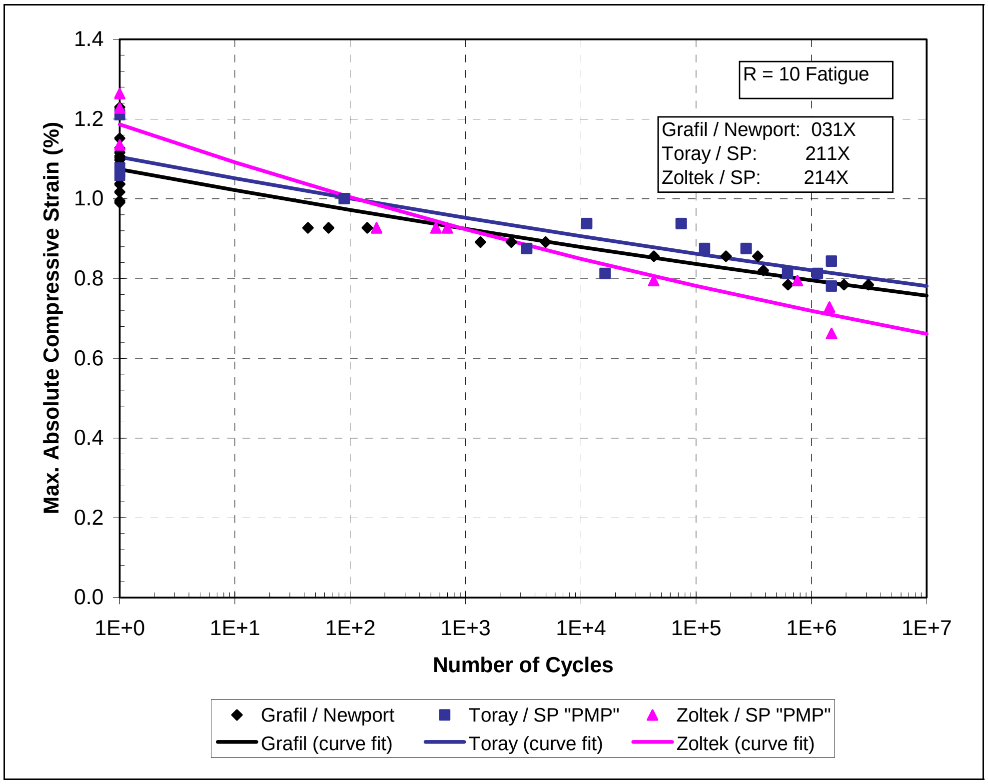

Figure 5-5. R = 10 Fatigue Data for Thin-Coupon Prepreg Panels

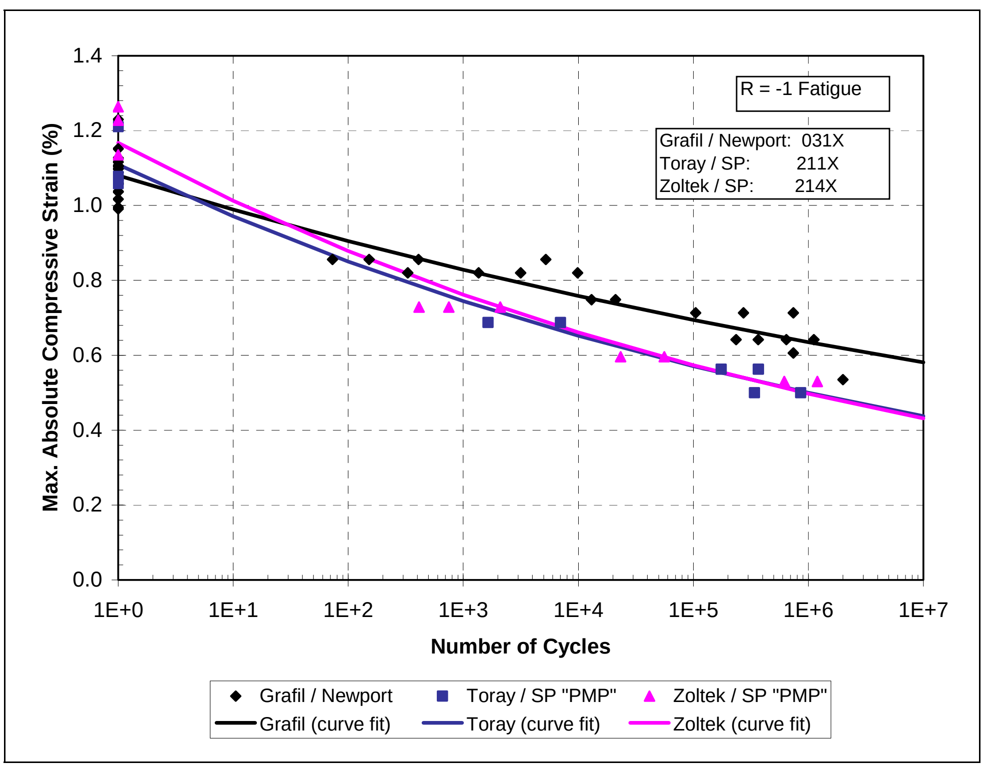

Figure 5-6. R = -1 Fatigue Data for Thin-Coupon Prepreg Panels

Table 5-8. Curve-Fit Parameters for Prepreg Carbon Thin Coupons

	R = 0.1				R = 10				R = -1	
Material	σ_o **(MPa)**	ε_o **(%)**	**m**	**A**	σ_o **(MPa)**	ε_o **(%)**	**m**	**A**	**m**	**A**
Grafil / Newport	1496.4	1.45	47.9	1.030	1047.0	1.08	46.1	0.992	26.0	0.998
Toray / SP	1980.9	1.52	31.4	1.020	1229.7	1.12	46.5	0.990	17.3	0.995
Zoltek / SP	1812.3	1.40	37.7	0.979	1257.8	1.21	27.6	0.982	16.2	0.966

5.1.2.4 Infused Carbon Fatigue Results

Figure 5-7 through Figure 5-10 present fatigue data for the VARTM-infused carbon-fiberglass triaxial fabric. Curve-fit parameters are listed in Table 5-9. The test panels include both epoxy and VE resins. It was noted in the above section on static strength testing that although the laminate schedule is identical for these panels, the differential in measured modulus results in different trends for stress and strain comparisons. Figure 5-7, Figure 5-8, and Figure 5-9 are plotted on the basis of stress, which is a more direct basis for comparing the load-carrying capability of the tested laminate.

In tension (R = 0.1), the fatigue performance of VE was clearly lower than epoxy. Figure 5-7 shows that the single-cycles stress for the infused VE material was slightly higher than that for the epoxy, but at a million cycles was about 25% lower.

Significantly different trends are seen in the fatigue stress data for compression and reversed loading, with a much smaller difference between the VE and epoxy results. Figure 5-8 shows that in R = 10 loading, the VE stress levels were consistently higher than the epoxy, with a differential of about 5% at low cycles, growing to more than 10% at high cycles. Figure 5-10 shows the R = 10 data plotted on the basis of stain. As expected, applying the higher compressive modulus in the VE strain calculations resulted in a shift between the curves. Calculated VE strains for R = 10 fatigue are about 7% lower than epoxy at low cycles, and 2% lower at high cycles.

Fatigue data for R = -1 (Figure 5-9) are relatively sparse, and show only modest difference in measured stress between epoxy and VE. The VE curve is steeper than that for epoxy, partly due to higher values of single-cycle stress. As noted above, applying the measured compressive modulus values to these curves would result in a downward shift of the calculated VE strains relative to the epoxy.

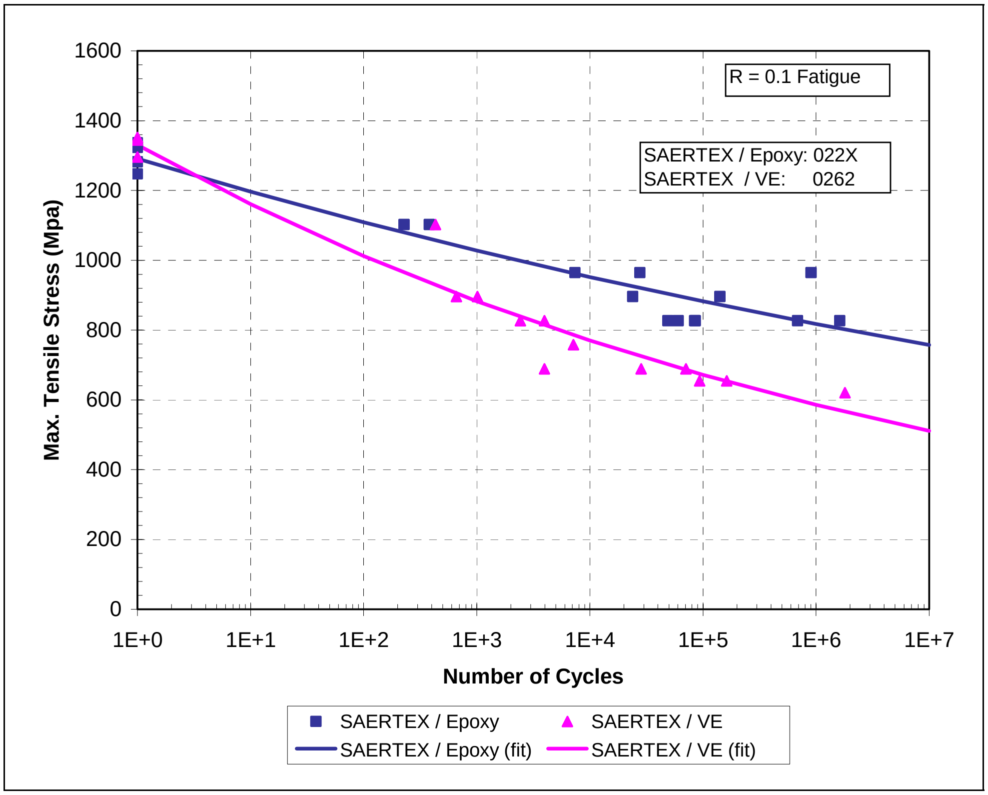

Figure 5-7. R = 0.1 Fatigue Data for VARTM Infused Carbon-Fiberglass Triaxial Fabric

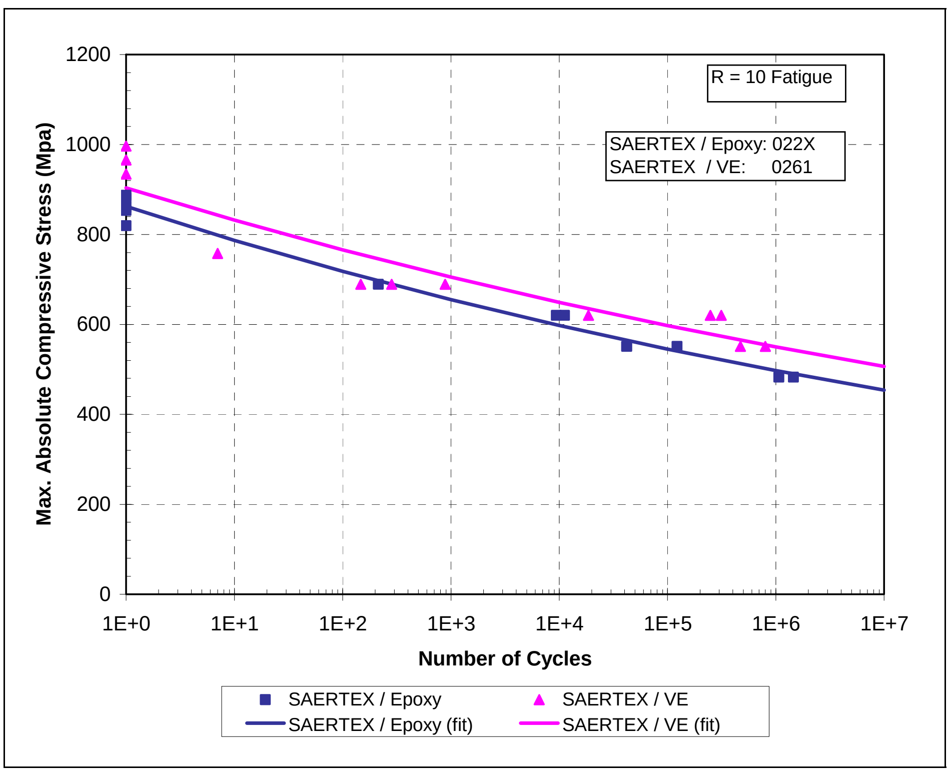

Figure 5-8. R = 10 σ-N Data for VARTM Infused Carbon-Fiberglass Triaxial Fabric

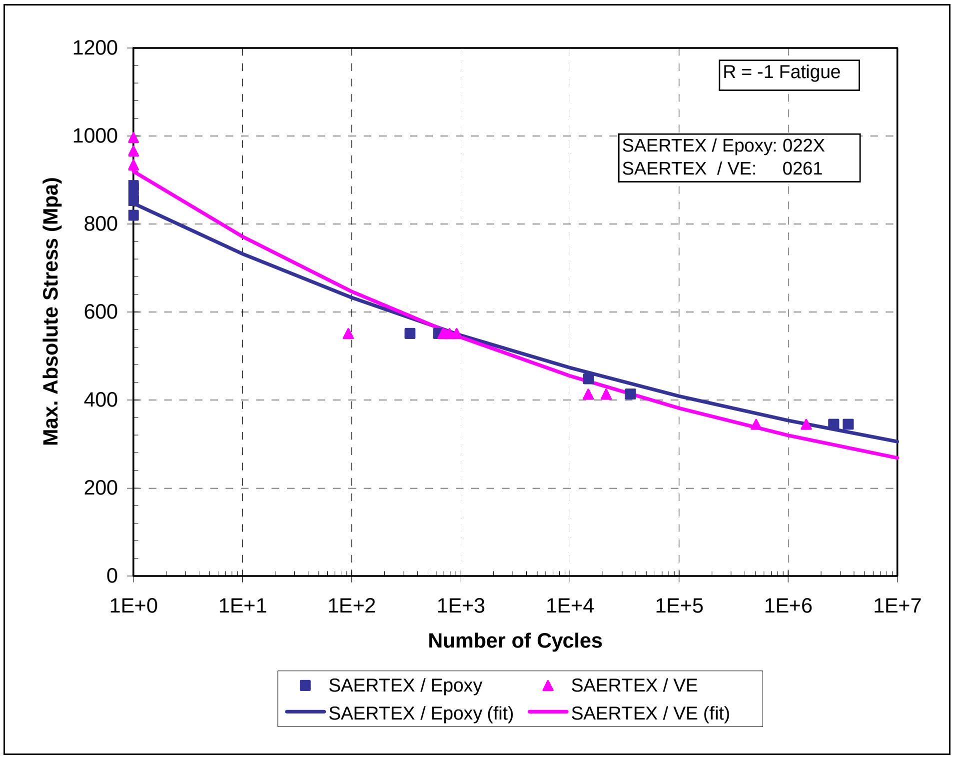

Figure 5-9. R = -1 σ-N Data for VARTM Infused Carbon-Fiberglass Triaxial Fabric

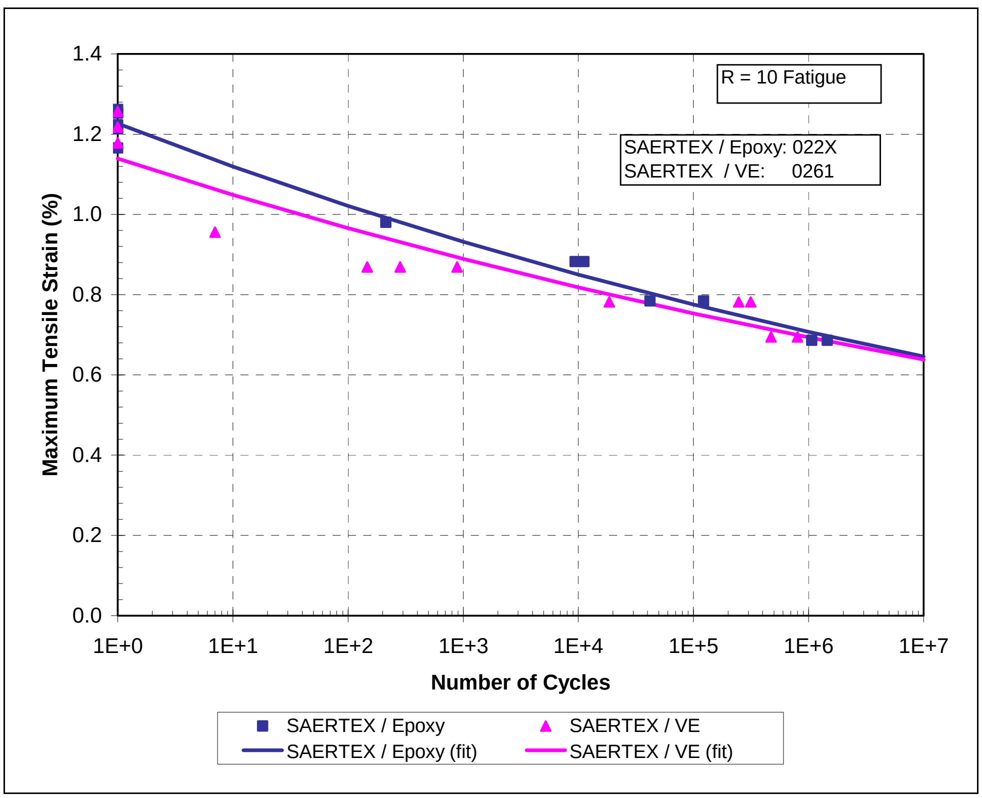

Figure 5-10. R = 10 ε-N Data for VARTM Infused Carbon-Fiberglass Triaxial Fabric

Table 5-9. Curve-Fit Parameters for Infused Carbon-Glass Triax Thin Coupons

	R = 0.1				R = 10				R = -1	
Material	σ_o (MPa)	ε_o (%)	m	A	σ_o (MPa)	ε_o (%)	m	A	m	A
SAERTEX / Epoxy	1297.0	1.68	30.2	0.995	859.9	1.22	15.8	0.985	25.1	1.003
SAERTEX / VE	1330.8	1.68	16.8	1.000	965.4	1.22	25.1	1.003	13.1	0.952

5.1.2.5 Comparison of Fatigue Data for Prepreg and Infused Materials

Figure 5-11 through Figure 5-13 show comparisons of fatigue data for prepreg and infused (epoxy) panels. The infused panels use the SAERTEX carbon-fiberglass triaxial fabric with a substantial amount of integral ±45° fiberglass fibers, whereas the prepreg panels are primarily unidirectional carbon tape, with a small amount of ±45° glass in the facings. Consequently, the modulus of the infused panels is by design lower than the prepreg materials. In terms of evaluating the performance of the carbon fibers in the laminate, a comparison of strain levels provides a more valid basis than does the stress.

Figure 5-11 compares the R = 0.1 data from the Toray prepreg and epoxy-infused triax panels. The overall performance for these materials is quite similar, with strain values for the infused article modestly higher than those for the prepreg over the entire range of cycles.

Figure 5-12 shows a somewhat different trend for R = 10 fatigue. At the single-cycle end of the ε-N curve, the infused triax panel strains are about 10% higher than the prepreg, but at 1E+6 cycles, the triax strains fall below the prepreg by 20%. The R = 10 slope is steeper for the infused material. The prepreg ε-N curve has a slope parameter of m ≈ 46, whereas the triax has an m ≈ 25.

Comparisons for R = -1 loading (Figure 5-13) show very close agreement between the infused material and the Toray prepreg. At the single-cycle end of the curve, the infused material has strains about 8% higher than the prepreg, and at high cycles, the two curves converge.

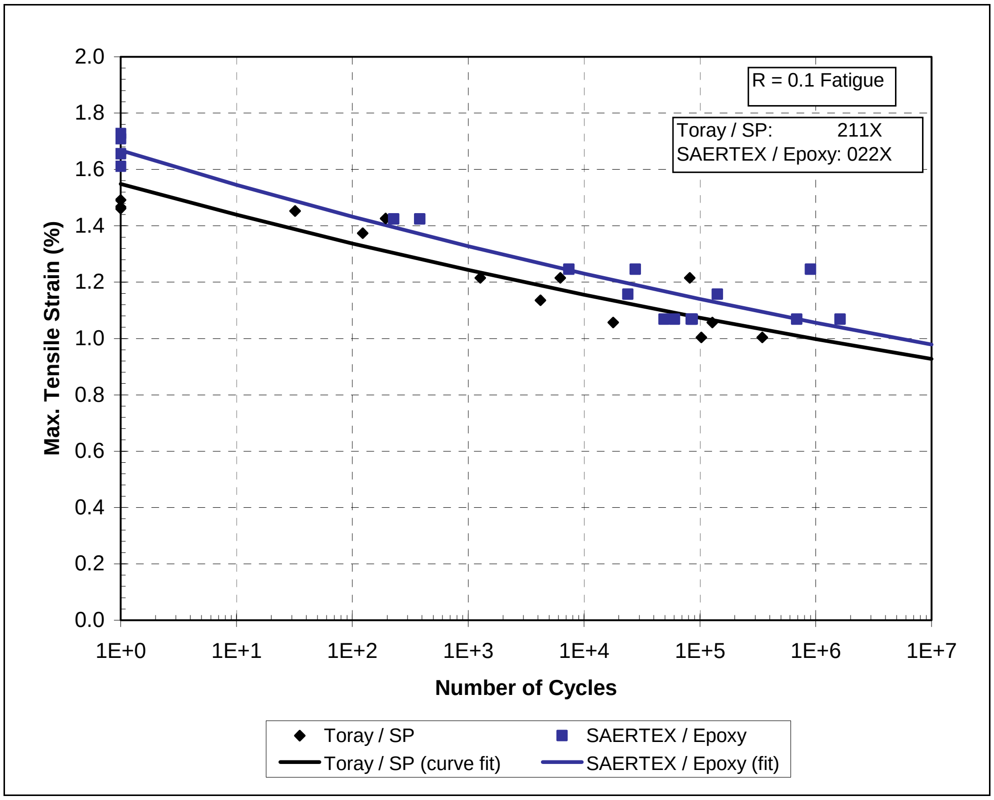

Figure 5-11. R = 0.1 Fatigue Data for Prepreg and Infused (Epoxy) Panels

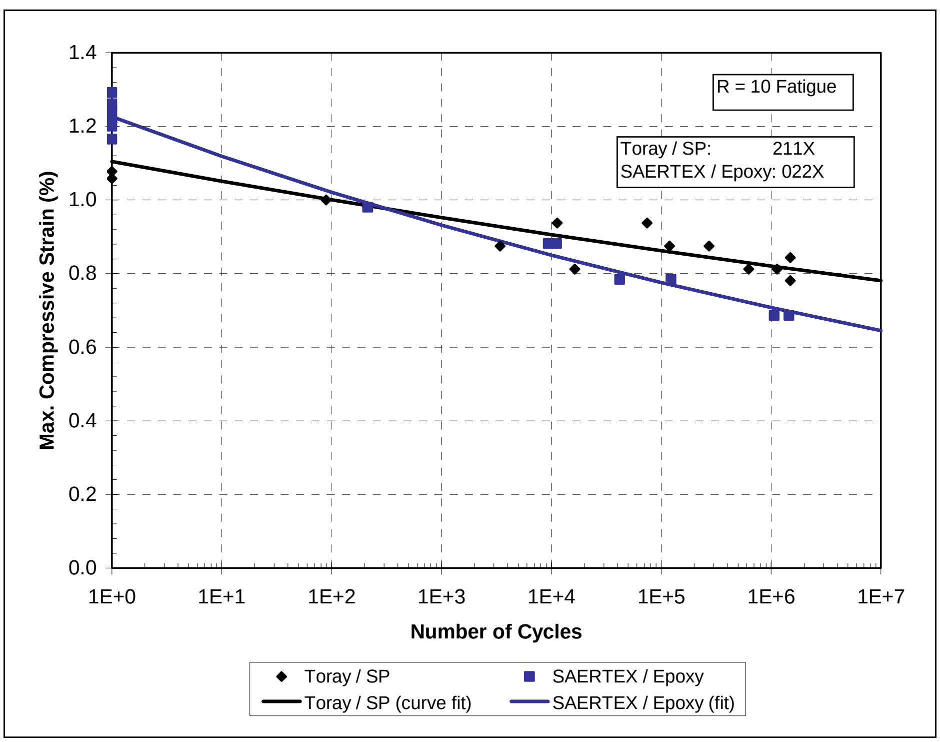

Figure 5-12. R = 10 Fatigue Data for Prepreg and Infused (Epoxy) Panels

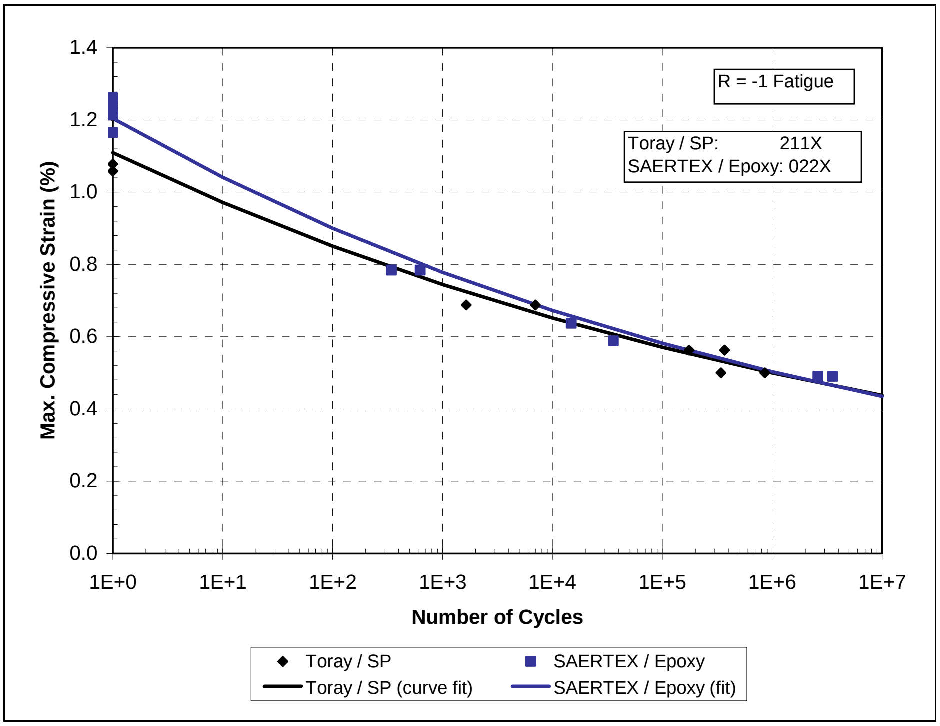

Figure 5-13. R = -1 Fatigue Data for Prepreg and Infused (Epoxy) Panels

5.2 Thick Coupon

5.2.1 Thick-Coupon Compressive Static Testing

As discussed above, initial thick-coupon testing has been performed for an epoxy-infused triax panel of 11.2-mm thickness. Initial compression testing was performed at Intec using a long dog-bone shaped specimen with custom-designed anti-buckling restraints (details depicted in Appendix B). Two attempts were made with this coupon geometry using two different designs for the anti-bucking fixture. Neither test was successful, with failures occurring near the grips at strain levels far below those achieved for the thin coupons.

Subsequently, the thick-coupon compressive testing was switched to use an ASTM D6641 coupon geometry and combined loading in compression (CLC) fixture. Seven 12.5-mm wide coupons and four 25-mm wide coupons were successfully tested at the WSU test facility using the CLC fixture shown in Figure 5-14. Test results are presented in
Table 5-10, and a typical failure is shown in Figure 5-15. As indicated by the tabular data, higher static strength was measured for the 25.4-mm wide coupons than for those with a 12.7-mm width. As a result, the 25.4-mm wide geometry was selected for ongoing testing of the thick coupons.

The compressive strain measured for the 12.7-mm and 25.4 mm wide thick-coupons is 29% and 19% lower, respectively, than that measured for the thin-coupon testing of the same material. Because of difficulties encountered with the thick-coupon testing, it is not known if these decreases in strain are due to scaling effects or testing issues.

Figure 5-14. D6641 (CLC) Thick-Coupon Test Fixture

Table 5-10. Thick-Coupon Static Test Results, WSU D6641 Testing

					(12.7-mm wide coupons)							(25.4-mm wide coupons)					
		Physical Properties			Mean Stress			Modulus		Strain	Mean Stress			Modulus		Strain
I.D.	Lab	υ_f (%)	ρ (g/cm^3)	T_g (C)	#	σ_X (Mpa)	COV (%)	E_X (Gpa)	COV (%)	ε_x (%)	#	σ_X (Mpa)	COV (%)	E_X (Gpa)	COV (%)	ε_x (%)
1211	WSU	56	1.676	72	7	632	11.5	80.6	3.7	0.78	4	709	12.3	80.0	3.5	0.89

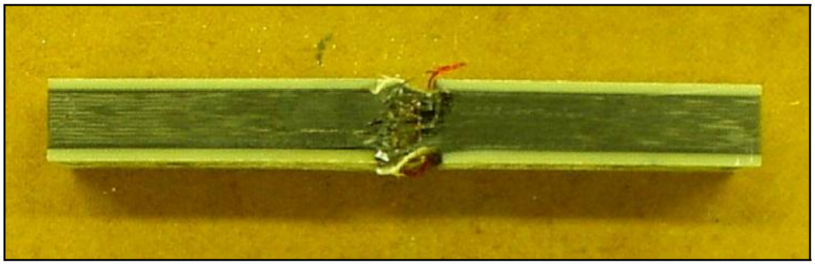

Figure 5-15. Thick-Coupon Gage Section Failure

5.2.2 Thick-Coupon Fatigue Testing

Following successful testing of the thick coupons in static compression, R = 10 fatigue testing was attempted using the same fixtures and specimen geometry. Initial tests resulted in failures in the tab region at load levels far below those expected for the material. It was determined that the stress concentration at the gage-section end of the tabs could be reduced by modifying the tab angle from 90° to 105°.

A new set of coupons was machined with the 105° tab angle; and fatigue testing was once again attempted. Although the modified coupons did not fail prematurely, the testing overloaded and damaged the CLC fixture. Based on these experiences, WSU opted to terminate both static and fatigue testing of thick coupons. No further effort was made for this type of article under the BSDS-II project.

5.3 Carbon Ply Drop

5.3.1 Prepreg Ply Drops

As noted in Section 4.5, ply drops were tested in both straight and pinked edge geometries. Figure 5-16 depicts a representative layup for a ply-drop panel The pinked ply-drop configuration is illustrated graphically in Figure 4-4, and a detailed panel specification (for infused SAERTEX material) is shown in Appendix C.

In general, asymmetries in the ply drop and ply transition panels created challenges for obtaining reliable results in compression testing. Therefore, the majority of fatigue testing was performed for R = 0.1. Similar trends could be expected for R = 10, and R = -1, with an overall reduction in the fatigue performance expected.

Figure 5-17 shows results for ply-drop panels manufactured at MSU using the Grafil/Newport prepreg material. The data represent the number of cycles required to develop a delamination of 6.35 mm. As seen in the figure, for the straight ply drop, the strain level for 1E+6 cycle delamination is below 0.3%. The fatigue performance for the pinked coupon is greatly improved, with 1E+6 strain increased to above 0.5%. Curve-fit parameters for all infused ply-drop panels are given in Table 5-11.

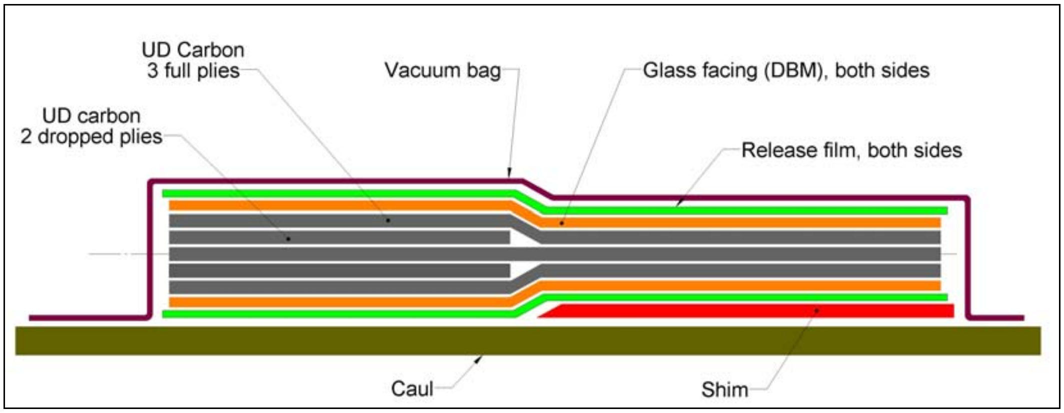

Figure 5-16. Representative Layup of Ply-Drop Panel

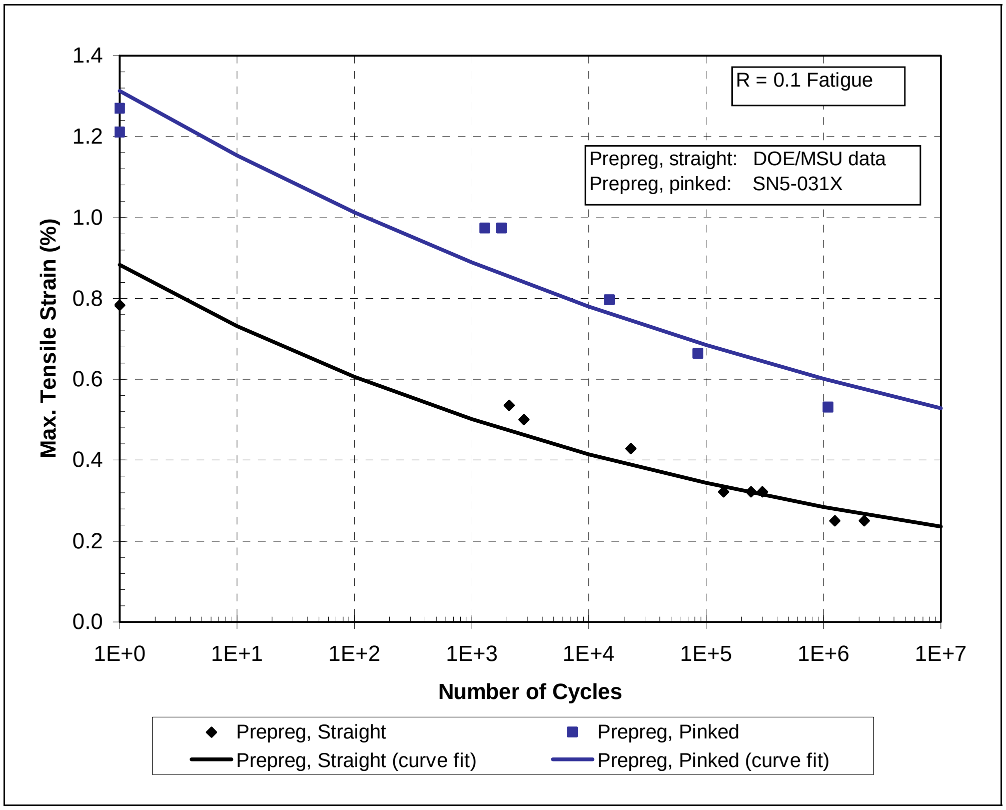

Figure 5-17. R = 0.1 Data for Prepreg Ply Drops

Table 5-11. Curve-Fit Parameters for Prepreg Ply-Drop Panels

	R = 0.1			
Drop Style	**σ_o (MPa)**	**ε_o (%)**	**m**	**A**
Straight	755.0	1.13	12.2	1.129
Pinked	965.0	1.24	17.7	1.059

5.3.2 Infused Ply Drops

Figure 5-18 and Figure 5-19 show results for ply-drop panels manufactured at TPI using the SAERTEX carbon-fiberglass triax fabric with both epoxy and VE resins, in both straight and pinked configurations. Curve-fit parameters for all infused ply-drop panels are given in Table 5-12.

The trends for both epoxy and VE resins are quite similar. For the straight-edge configuration, the 1E+6 strain is about 0.3%, and only slightly higher for the epoxy resin than for VE. The improvement due to pinking is less than was seen for the prepreg materials, with 1E+6 strain values increasing to about 0.4% for both epoxy and VE.

The relatively low fatigue performance for the infused ply drops with pinking may be partly due to the geometry of the ply drops and panels. Carbon fiber is difficult to cut, and Figure 5-20 shows that the accuracy of the pinking in the SAERTEX fabric was far from ideal. By contrast, the tacky nature of prepreg materials makes precise cutting much easier, as evidenced in Figure 5-21.

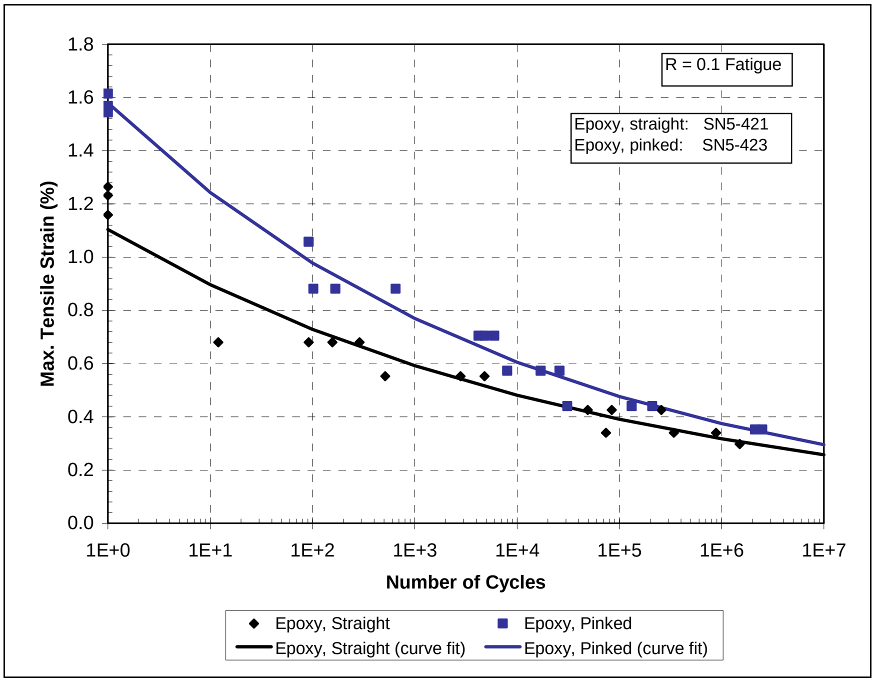

Figure 5-18. R = 0.1 Data for Infused Epoxy Ply Drops

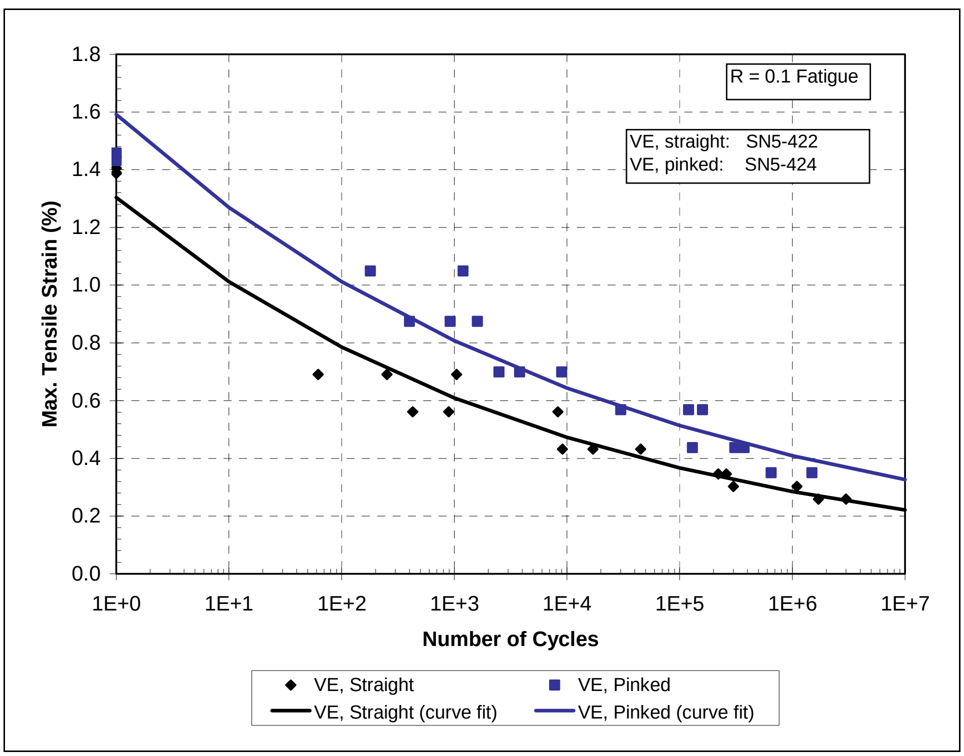

Figure 5-19. R = 0.1 Data for Infused VE Ply Drops

Table 5-12. Curve-Fit Parameters for Infused Ply-Drop Panels

		R = 0.1			
Resin	**Drop Style**	**σ_o (MPa)**	**ε_o (%)**	**m**	**A**
Epoxy	Straight	987.0	1.22	11.1	0.906
Epoxy	Pinked	1232.0	1.58	9.6	1.003
VE	Straight	1112.5	1.39	9.1	0.935
VE	Pinked	1141.1	1.45	10.2	1.100

The infusion process also presented challenges for obtaining good symmetry through the coupon thickness. By design, the VARTM process has a hard surface (mold) on the bottom and a soft surface (vacuum bag) on the top. As a result, it is difficult to obtain the same geometry on both surfaces. While several shimming approaches were tried, the best on the infused panels has less-than-ideal symmetry. This is illustrated in Figure 5-22, where a wide variation of asymmetry is seen.

During testing, MSU documented that the coupon asymmetry played a role in the failure progression. Figure 5-23 details the delamination in the panel with straight ply drop and VE resin. The figure shows that the face with the most extreme geometry change (thin section to thick) delaminated first. Under continued fatigue testing, it was observed that out-of-plane movement caused the other face to delaminate.

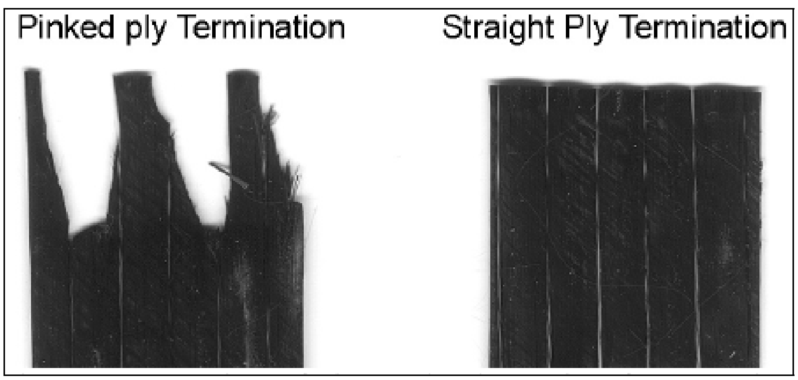

Figure 5-20. Face View of Ply Terminations Taken from Matrix Digestion Coupons

Figure 5-21. Face View of Prepreg Pinked Ply Termination

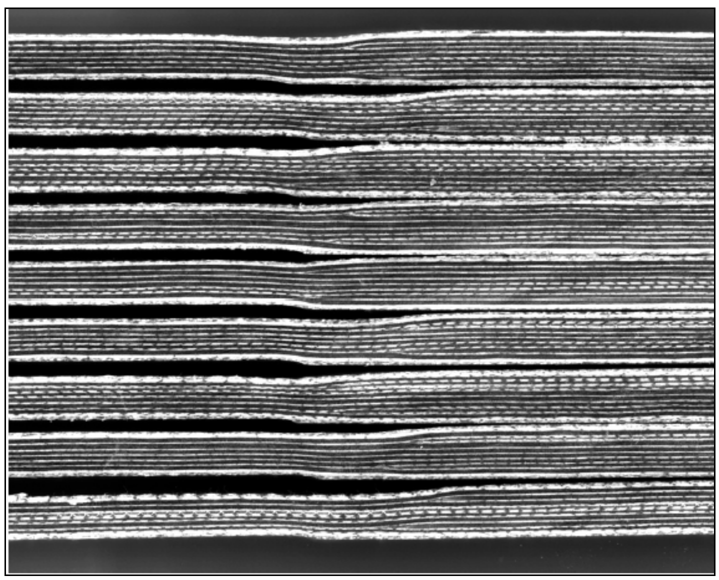

Figure 5-22. Edge View of Material 422 (Straight-Edge, VE) Coupons Showing Asymmetry

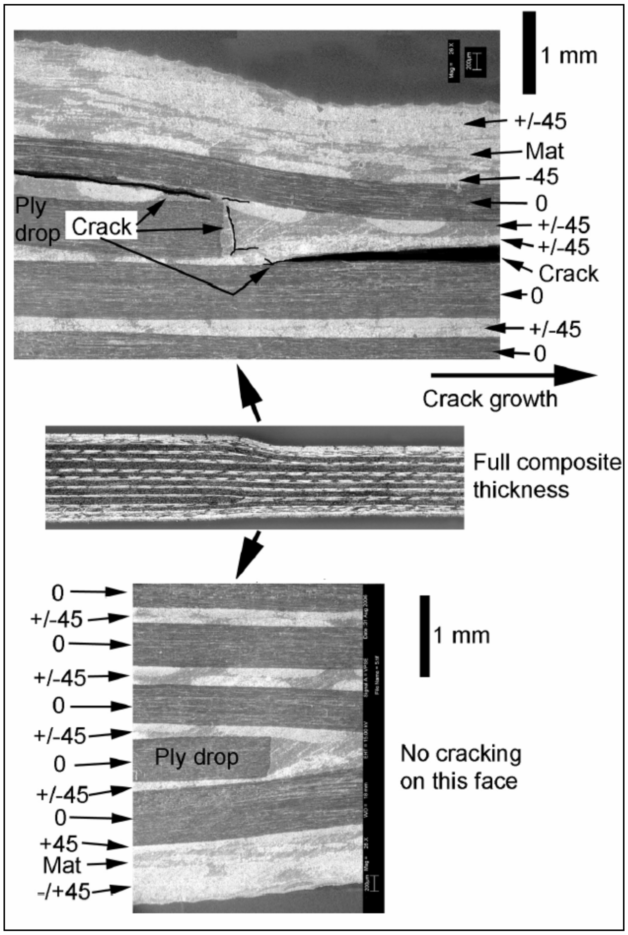

Figure 5-23. Material 422 (Straight-Edge, VE) Showing Ply Delaminations

5.4 Carbon-Fiberglass Ply Transition

5.4.1 General

As discussed in Section 4.6, the test matrix includes the evaluation of carbon-to-fiberglass ply transitions, as this is considered to be an important structural detail for the integration of carbon fiber materials into wind turbine blades. Figure 4-5 shows a conceptual illustration of such a detail in a blade structure.

Two methods of testing these details have been considered during this project. The first is axial testing of a coupon that includes a ply-transition detail. Challenges with this approach include the need to maintain symmetry of the coupon, and limitations to the overall ply number and consequential limitations on the ratio of continuous versus transitioned plies. The second method considered is a 4-point bending test of a box-beam with spar structure. This approach eliminates the need for axial symmetry of each spar, and the overall structure more closely mimics that of a turbine blade. However, this approach has additional cost and complexity concerning the design of shear webs, load introduction, and other details.

In the end, all ply-transition tests were conducted in axial loading. Figure 5-24 illustrates the general arrangement of the panel layup. The ply transition panels include several details which proved challenging for design and testing. First, the stiffness of unidirectional fiberglass is about 1/3 of that for carbon fibers. Therefore, maintaining continuity of stiffness across the ply transition would require that a dropped carbon ply be replaced by plies of approximately three times the carbon ply thickness. This was accomplished by the addition of “doubler” plies of fiberglass as shown in Figure 5-24.

A related issue is the motivation to avoid the introduction of misalignment in the unidirectional plies. Because carbon fibers are recognized to be more sensitive than fiberglass to misalignment, the initial design philosophy was to keep the glass doublers to the exterior of the carbon plies (see Figure 5-24).

Initial testing with this feature resulted in a failure mode being introduced at the glass doublers. As a result, the panels were re-designed so that glass doublers were located inside the outer-most carbon plies (see Figure 5-25). Although this introduced a slight “jog” in the outer carbon plies, the redesigned transition exhibited improvements in failure mode and corresponding strength. These trends are discussed in greater detail in the following sections.

Note that although the Figure 5-24 caption and subsequent discussion refers to an “exterior” doubler, this does not imply that the doublers were the outer-most lamina in the panel. In all cases, a final ply of double-bias material was used to cover the unidirectional materials. The use of “interior” and “exterior” for doublers describes their placement relative to the carbon unidirectional layers.

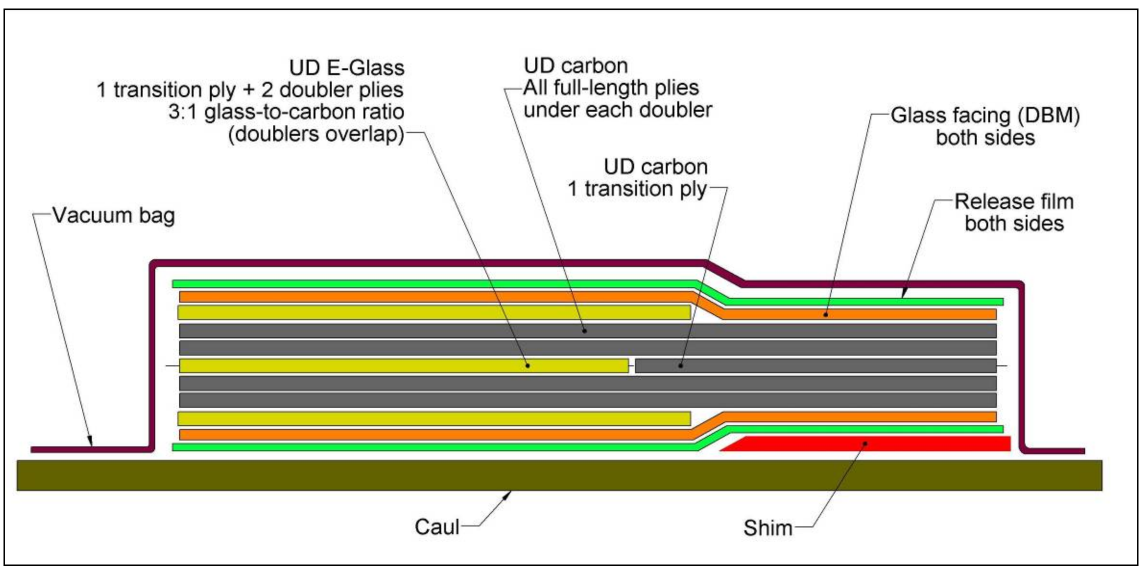

Figure 5-24. Representative Layup of Ply-Transition Panel (Initial Design, Exterior Doublers)

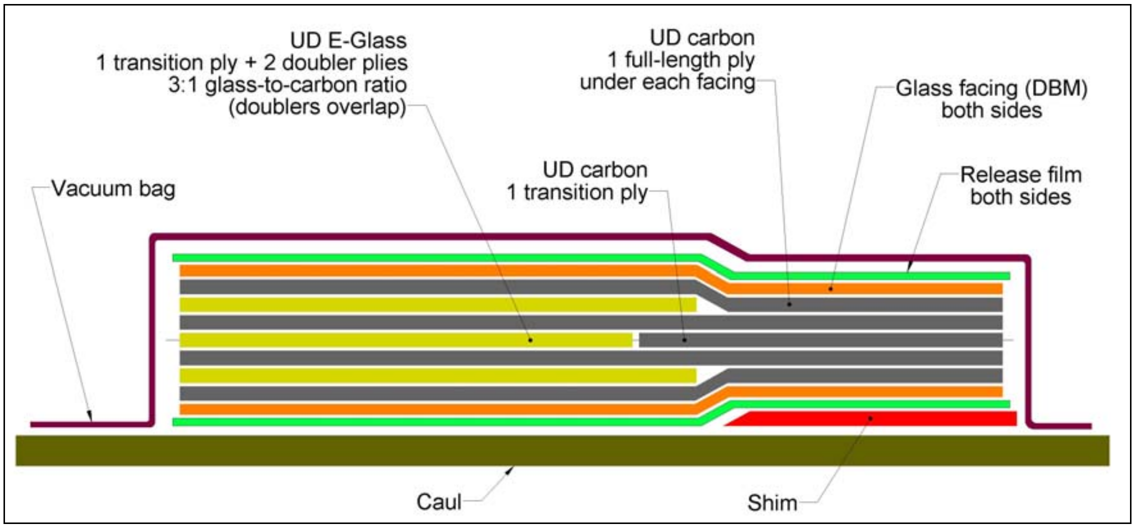

Figure 5-25. Representative Layup of Ply-Transition Panel (Redesign, Interior Doublers)

5.4.2 Infused Ply Transitions

The initial ply-transition panels tested under this program were infused at TPI using the SAERTEX carbon-fiberglass triax fabric with epoxy resin. The conceptual design of the ply transition was as shown in Figure 5-24, with an exterior doubler arrangement.

Performance of the initial infused ply-transition panels was unexpectedly poor. The results were mainly attributed to the axial symmetry of the panels and the exterior location of the doublers. Figure 5-26 shows typical cross-section views of the infused ply transition panels. As seen in the figure, the panels tended to be asymmetric, with a pronounced step on one surface and a minimal step on the opposite surface.

MSU noted that the failure sequence was consistently related to this asymmetric geometry. Figure 5-27 shows the typical delamination sequence observed during tensile testing. In all test articles, the ply delamination started between the first dropped zero-degree ply and the second, continuous zero-degree ply on the “smooth” side of the coupon (see Figure 5-27). The opposite side with the more abrupt step did not begin to delaminate until the first side was significantly delaminated.

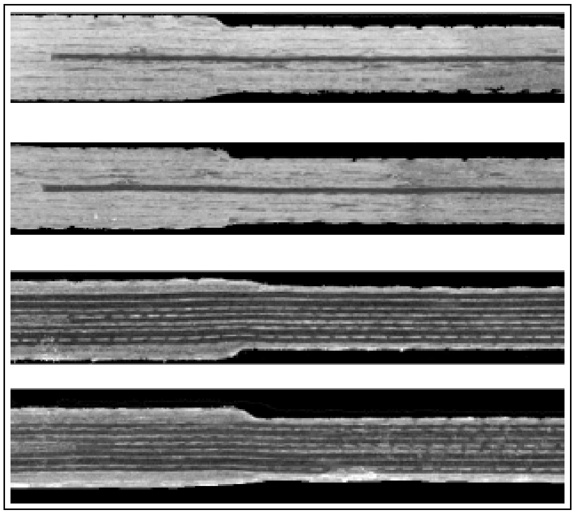

Figure 5-26. Typical Cross-Sections for Infused Ply Transitions (Top 2 Mostly Glass, Bottom 2 Mostly Carbon)

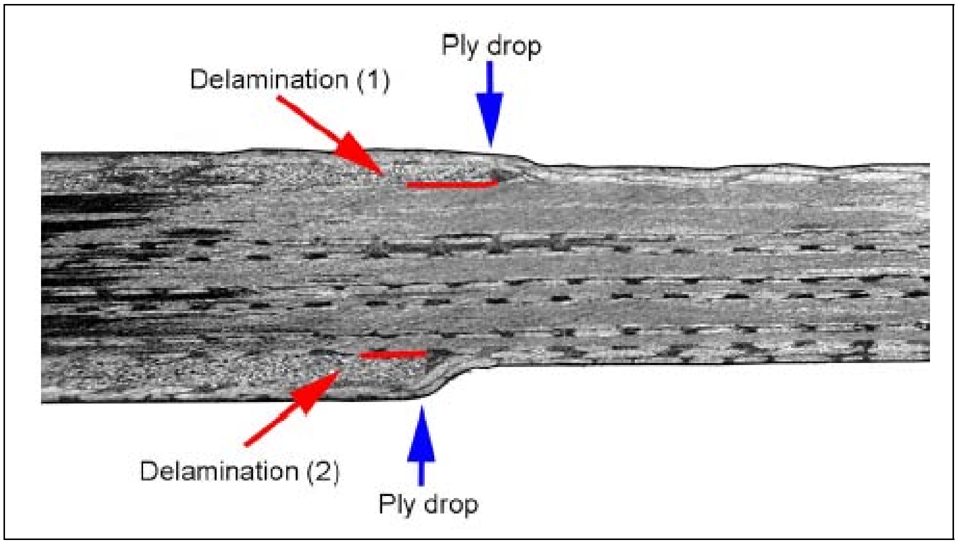

Figure 5-27. Typical Ply Delamination Sequence

Table 5-13 shows the average static tensile strength data measured for the infused transition panels. In general, the strain levels to delamination were very low for tensile testing. MSU was unable to run compression tests due to the asymmetry of the coupon taper.

Table 5-13. Static Tensile Data for Infused Carbon-Fiberglass Ply Transition Panels

	Modulus (GPa)		Max. Stress (MPa)		Max. Strain (%)	
Configuration	Thin Side	Thick Side	Thin Side	Thick Side	Thin Side	Thick Side
Mostly Carbon	83.2	71.1	952.4	-	1.06	-
Mostly Glass	42.9	39.5	493.4	-	1.21	-

A second-iteration design was developed for the infused ply-transition panels. These articles were fabricated and delivered to MSU in December 2006. However, in exploratory cuts MSU discovered an error in the as-built laminate schedule that they concluded would lead to an undesirable failure mode. As such, testing of the second-iteration infused panels is not planned to proceed.

5.4.3 Prepreg Ply Transitions

Based on the lessons learned from the initial infused articles, the transition panels were redesigned and fabricated at MSU using prepreg material. The carbon material was the same as used in the MSU ply-drop articles (Grafil fiber with Newport prepreg resin). The fiberglass materials were also impregnated by Newport. As discussed in Section 4.6, ply transition panels were fabricated in both mostly glass and mostly carbon configurations. Additionally, two layup schedules were used, transitioning either one or two plies. In an attempt to delay the onset of delamination, the fiberglass doublers were moved to the interior of the unidirectional fabric stack as indicated in Figure 5-25. Detailed panel specifications for prepreg one- and two-ply transition panels are shown in Appendix C.

Figure 5-28 shows results for ply-transition panels manufactured at MSU. As in the ply-drop tests, the data represent the number of cycles require to develop a delamination of 6.35 mm. Curve-fit parameters for the infused ply-transition panels are given in Table 5-14.

The figure shows a significant reduction in fatigue performance in going from one to two ply transitions (mostly glass data). However, the tensile strain values for delamination at 1E+6 cycles is close to 0.5%, which compares somewhat favorably with results for the ply-drop coupons.

As of this report date, testing at MSU is ongoing for prepreg transition panels at R = 10 and R = -1. Results from these tests will be reported by MSU as part of the ongoing development of the DOE/MSU Database [10].

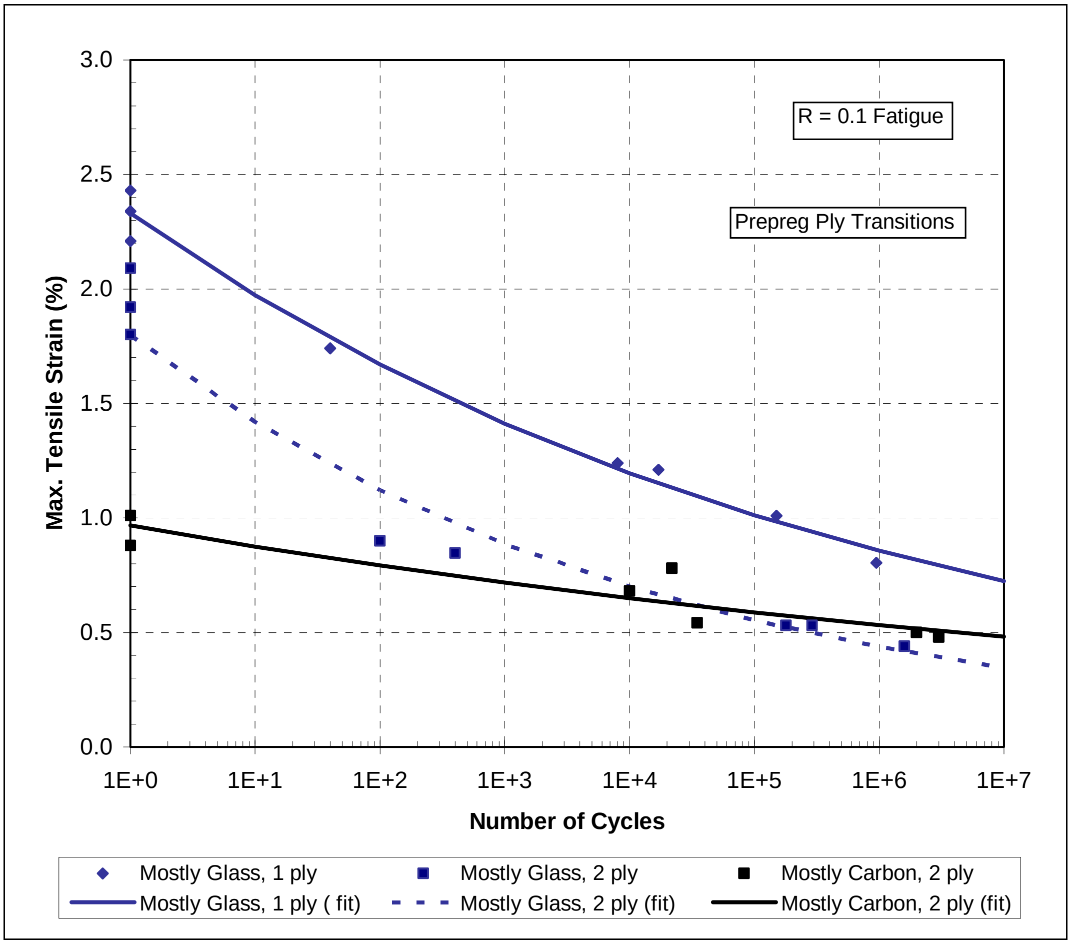

Figure 5-28. R = 0.1 Data for Prepreg Ply-Transition Panels

Table 5-14. Curve-Fit Parameters for Infused Ply-Transition Panels

		R = 0.1			
Style	**Plies Transitioned**	**σ_o (MPa)**	**ε_o (%)**	**m**	**A**
Mostly Glass	1	818.5	2.33	13.8	1.002
Mostly Glass	2	701.4	1.78	9.8	1.008
Mostly Carbon	2	917.6	0.95	23.1	1.020

Section 6 - Observations and Conclusions

This report summarizes the results from coupon and subscale testing of carbon-fiber composites for potential use in wind turbine blades. Initial thin-coupon static testing included a wide range of parameters, including variation in manufacturer, fiber tow size, process, fabric architecture, and resin type. A smaller set of these materials and process types was also evaluated in thin-coupon fatigue testing, and in ply-drop and ply-transition panels. The majority of materials used epoxy resin, with VE resin also used for selected cases. Late in the project, testing of unidirectional fiberglass was added to provide an updated baseline against which to evaluate the carbon material performance.

6.1 Thin Coupon Static

6.1.1 Carbon Fiber

Thin-coupon testing of prepreg materials showed little variation in static strength with manufacturer or tow size. Average values for compressive static strain were typically in the range of 1.0%-1.1%.

The SAERTEX carbon-fiberglass triaxial fabric with epoxy infusion achieved static strain values similar to prepreg materials. However, because of the inclusion of the ±45° glass, the modulus and stress at failure are both lower than for the unidirectional carbon prepreg. These results show that the carbon fibers in the infused laminate are reaching performance levels comparable to that of a unidirectional prepreg.

With VE infusion, the SAERTEX triaxial materials achieved slightly higher compressive static strength than that of the epoxy-infused articles. However, the compressive modulus measured by Intec for the VE infused panels was 13% higher than measured for the epoxy material. As a result, the calculated static compressive strain was 8% lower for the VE coupons.

Because the fabric was the same in both cases, and the measured panel thickness and fiber volume fractions were nearly identical, the large difference in modulus would not be expected. In general, the stress measurement which is based on applied load is more reliable than the compressive modulus measurement, which is based on a strain gage on a small specimen. Nonetheless, to maintain consistency in the presentation and analysis of data, GEC has used measured compressive modulus to calculate compressive strain.

6.1.2 Fiberglass

Static testing was performed for the E-LT-5500 fiberglass fabric, infused with both epoxy and VE resin. In general, the fiberglass material showed good performance in static strength for both epoxy and VE. Average tensile strain approached 2.3% for both resin systems, with very low coefficients of variation (COV ≤ 2%). Average compressive strains were only slightly lower at approximately 2.2%.

6.2 Thin-Coupon Fatigue

6.2.1 Carbon Fiber

Two styles of carbon fiber were tested in a prepreg form: Toray T600 (24k) and Zoltek Panex 35. Each of these fibers was impregnated by SP Systems, using their WE90-1 resin and PMP process. A third data set was provided by MSU for comparative purposes, fabricated from Grafil 34-600 fibers (48k) and Newport NB307 resin. For all three prepreg materials, thin-coupon fatigue testing was performed at R = 0.1, 10 and -1. In general, the three prepreg carbon materials showed very similar fatigue performance. No consistent trend was seen concerning tow size.

Epoxy-infused (SAERTEX triax) fabric preformed fairly well in fatigue relative to the prepreg materials. At R = 0.1, the infused material strains were modestly higher than the Toray/SP prepreg. For R = -1, the infused material strains were slightly higher at low cycles, and converged with the prepreg strains at high cycles. A different trend was seen for R = 10 fatigue At the single-cycle end of the ε-N curve, the infused triax panel strains are about 10% higher than the prepreg, but at 1E+6 cycles, the triax strains fall below the prepreg by 20%.

For the infused carbon panels in tension (R = 0.1), the fatigue performance of VE was generally lower than epoxy. The single-cycles stress for the infused VE material was slightly higher than for the epoxy, but was about 25% lower at a million cycles.

Significantly different trends are seen in the fatigue stress data for compression and reversed loading, with a much smaller difference between the VE and epoxy results. In R = 10 loading, the VE stress levels were consistently higher than the epoxy, with a differential of about 5% at low cycles, growing to more than 10% at high cycles. Fatigue data for R = -1 are relatively sparse and show only modest difference in measured stress between epoxy and VE. The VE curve is steeper than that for epoxy, partly due to higher values of single-cycle stress. As noted above, applying the measured compressive modulus values to these curves would result in a downward shift of the calculated VE strains relative to the epoxy. Because the static testing at Intec had measured higher modulus values for the infused VE panels than for the epoxy, a strain-based compression tends to shift all the VE curves downward relative to the epoxy data.

6.2.2 Fiberglass

Fatigue testing was also performed for the E-LT-5500 fiberglass fabric, infused with both epoxy and VE resin. In both tension and compression, the single-cycle strain values showed modest variation between the epoxy and VE resins. The single-cycle tensile strain was higher than the static value measured at Intec, and the compressive single-cycle strains were lower than the corresponding static measurements.

Several trends were noted for the tension (R = 0.1) ε-N curve. For both the epoxy and VE resins, the intersect of the curves at zero cycles is substantially higher than the measured single-cycle strain. This behavior is also indicated by the high values of the "A" curve-fit parameter for the R = 0.1 data. At higher cycles, the VE tension fatigue strength falls consistently below that of the epoxy. For the VE data, the tensile strain at 1E+6 cycles was somewhat low at a value of about 0.6%.

Significantly different trends are seen for the compressive fatigue data (R = 10). Most notable is that the VE data are consistently above that of the epoxy. The curves are also flatter, and the predicted strain levels at 1E+6 cycles are meaningfully higher than those seen for the R = 0.1 data. However, a careful comparison the tension and compression data indicates that this may be an artifact of the sparseness of the R = 10 data sets combined with the relatively flat slope for the curve fits.

6.3 Thick Coupon

Obtaining reliable results for thick coupons proved difficult. Using the ASTM D6641 coupon geometry and combined loading in compression (CLC) fixture, seven 12.5-mm wide coupons and four 25-mm wide coupons were successfully tested at the Wichita State University (WSU). Subsequent attempts to conduct fatigue testing with the D6641 coupon caused damage to WSU’s CLC fixture and as a result thick-coupon testing was terminated.

6.4 Carbon Ply Drop

In general, asymmetries in the ply drop and ply transition panels created challenges for obtaining reliable results in compression testing. Therefore, the majority of fatigue testing was performed for R = 0.1. Similar trends could be expected for R = 10, and R = -1, with an overall reduction in the fatigue performance expected. In performing the ply-drop tests, “failure” was determined by the number of cycles require to develop a delamination of 6.35 mm.

For all fabric and resin styles, a ply drop with a straight edge resulted in low fatigue performance. For prepreg laminate, the introduction of a pinked-ply drop edge nearly doubled the strain level for delamination at 1E+6 cycles. With the infused fabrics, the pinked edge showed far less benefit, with a strain improvement at 1E+6 cycles of only about 25%.

The relatively low fatigue performance for the infused ply drops with pinking may be partly due to the geometry of the ply drops and panels. Visual inspection after resin burn-off showed that the shape of the “pinked” fabric was significantly better for the prepreg than for the infused articles. MSU also noted the contribution of through-the-thickness asymmetry to the failure mode of the infused ply-drop articles.

6.5 Carbon-Fiberglass Ply Transition

It is expected that carbon-to-fiberglass ply transitions will be of high interest as blade designers seek to optimize the use of carbon fiber in wind turbine blades. Panels were fabricated for axial testing in an attempt to quantify the performance of such a feature. As in the ply-drop tests, panels were evaluated based on the cycles required to develop a delamination of 6.35 mm.

Ply-transition panels were fabricated in two basic configurations. One was designated mostly carbon, in which the article might represent the first carbon ply being transitioned to fiberglass in a carbon spar cap. The other was designated mostly fiberglass, and would represent the last carbon ply being transitioned. These two arrangements were considered as the bounding cases for the carbon-to-glass transition of a structural spar. Both of these configurations were fabricated in prepreg and infused articles. For the prepreg transition panels manufactured at MSU, two layup schedules were used, transitioning either one or two plies.

Initial ply-transition panels were infused by TPI using the SAERTEX carbon-glass triaxial fabric. Testing at MSU showed unexpectedly poor performance in tensile strength, with delaminations initiating at relatively low strain values. The early delamination was attributed primarily to asymmetry in the thickness taper and the placement of fiberglass doublers at the outer-most location in the stack of unidirectional plies. Based on the lessons learned from the initial infused articles, the transition panels were redesigned and fabricated at MSU using Grafil/Newport prepreg material. In an attempt to delay the onset of delamination, the fiberglass doublers were moved to the interior of the unidirectional fabric stack.

R = 0.1 testing of the second-iteration prepreg panels has been completed at MSU. The data show a significant reduction in fatigue performance in going from one to two ply transitions (mostly glass data). However, the tensile strain values for delamination at 1E+6 cycles is close to 0.5%, which compares somewhat favorably with results for the ply-drop coupons.

As of this report date, testing at MSU is ongoing for prepreg transition panels in compression, and for second-iteration epoxy-infused ply-transition panels at R = 0.1, 10, and -1. Results from these tests will be reported by MSU as part of the ongoing development of the DOE/MSU Database.

6.6 Summary

A range of carbon fiber styles and tow sizes were tested in prepreg form, and were generally found to have little variation in performance.

Numerous unidirectional carbon fabrics were considered for evaluation with VARTM infusion. Most fabric styles considered suffered either from poor infusibility or waviness of fibers combined with poor compaction. The exception was a triaxial carbon-fiberglass fabric produced by SAERTEX. This fabric became the primary choice for infused articles throughout the test program. The generally positive results obtained in this program for the SAERTEX material have led to its being used in innovative prototype blades of 9-m [11,12] and 30-m [13] length.

Infused articles were tested with both epoxy and VE resin systems. Comparisons between prepreg and infused epoxy, and between infused epoxy and VE were somewhat complex. In some cases, the performance variations were minimal and in other instances they were quite significant. For complex articles (ply drops and ply transitions), the comparison between prepreg and VARTM articles was complicated by the relative lack of symmetry in the infused articles.

The testing performed in this program has substantially added to the public-domain data for carbon fiber materials suitable for use in wind turbine blades. While numerous challenges were encountered during the course of this project, the results are nonetheless expected to be of value to the wind turbine blade design community.

Section 7 - References

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Appendix A

Original Planned BSDS-II Test Matrix

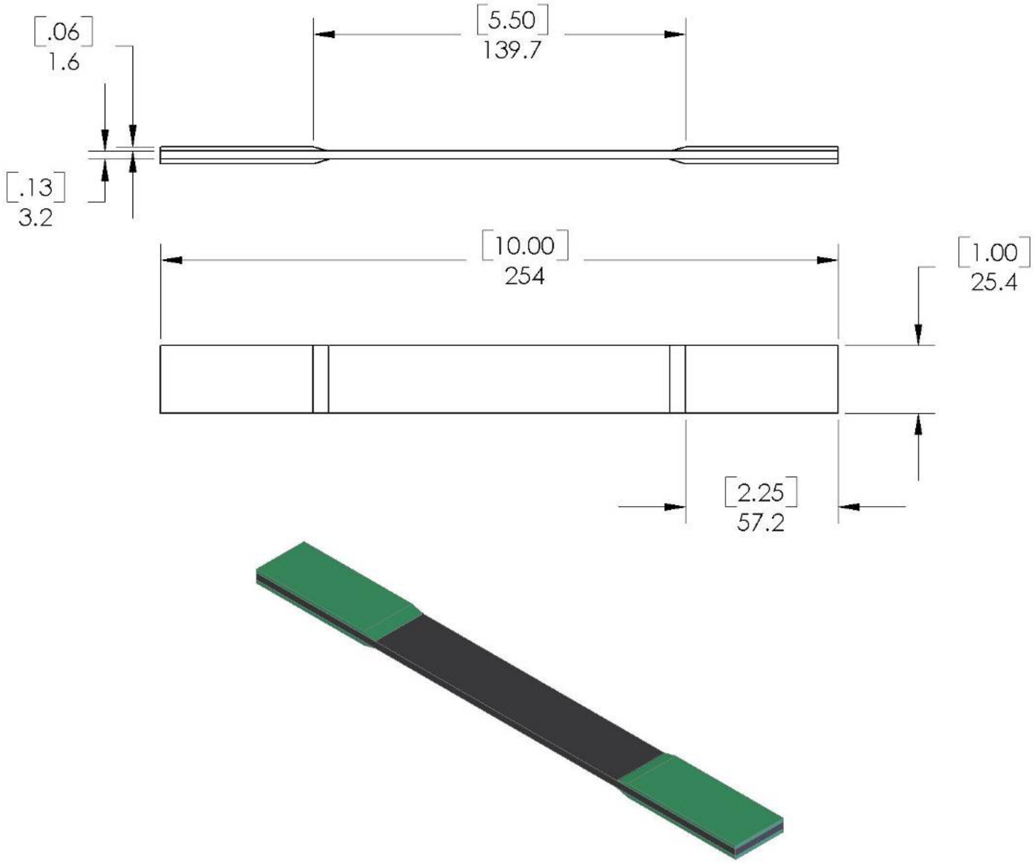
Test	Assumptions	# of Tests Planned
Thin coupon, static	5 tensile, 5 compressive	10
Thin coupon, S-N curve to 10^6 cycles (single R value)	4 ea. at 3-4 stress levels	4
Add S-N data to 10^7 cycles (single R value)	4 ea. at 10^7 stress level	0
Thin P4A coupon, static	5 tensile, 5 compressive	0
Thin P4A S-N curve to 10^6 cycles (single R value)	5 ea. at 3-4 stress levels	0
Thin coupon with single ply drop / transition, static	5 tensile, 5 compressive	4
Thin coupon with single ply drop / transition, S-N to 10	4 ea. at 3-4 stress levels	4
Thick laminate, static compression	5 specimens	4
Thick laminate with transition or ply drops, static	5 specimens	4
Thick laminate with transition or ply drops, S-N to 10^6	4 ea. at 3 stress levels	4
4-point beam with uniform cap laminate, static	Single article to failure	1
4-point beam with uniform cap laminate, fatigue	Single article to 10^6	0
4-point beam with cap laminate details, static	Single article to failure	1
4-point beam with cap laminate details, fatigue	Single article to 10^6	0
Biased material tube in axial / torsion loading, static	5 specimens	2
Biased material tube in axial / torsion loading, fatigue	4 ea. at 3 stress levels	1
Thick laminate + defects in static compression	5 specimens	3
Thick laminate + defects in fatigue	4 ea. at 3 stress levels	0
Determine margins / safety factors	Assigned low priority	0
Lap shear tests of bonding compounds	Assigned low priority	0

Appendix B

Summary of Coupon Geometry and Test Fixtures

ASTM D3039 Static Compression Coupon, Typical

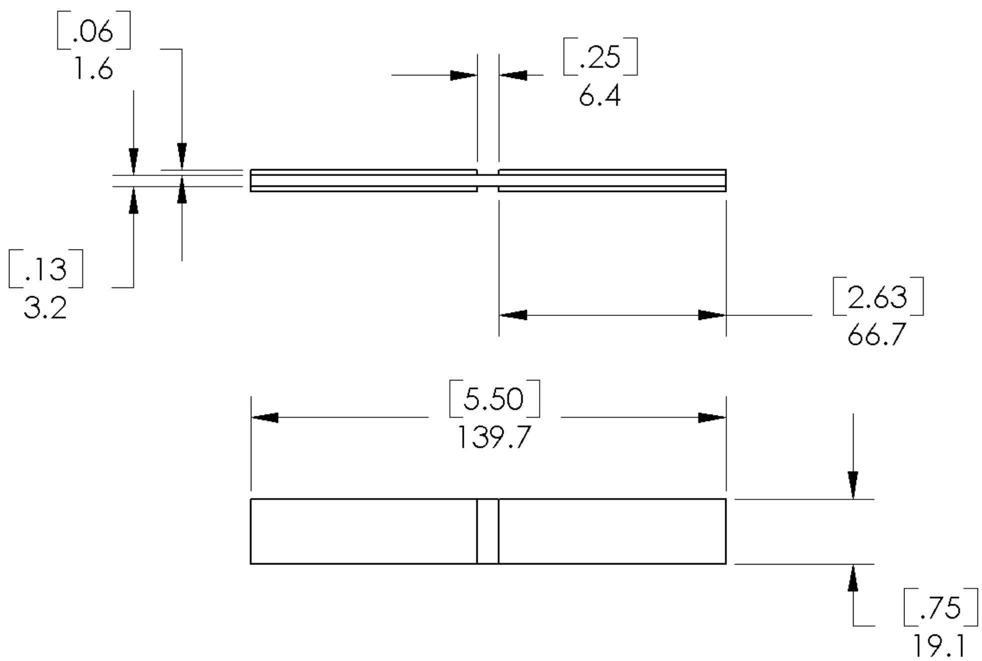
- Thickness varies with laminate
- Tab angle varies from 5 deg. to 90 deg.
- Typical load introduction is through hydraulic grips (shear loading)

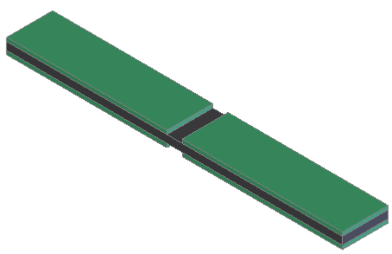


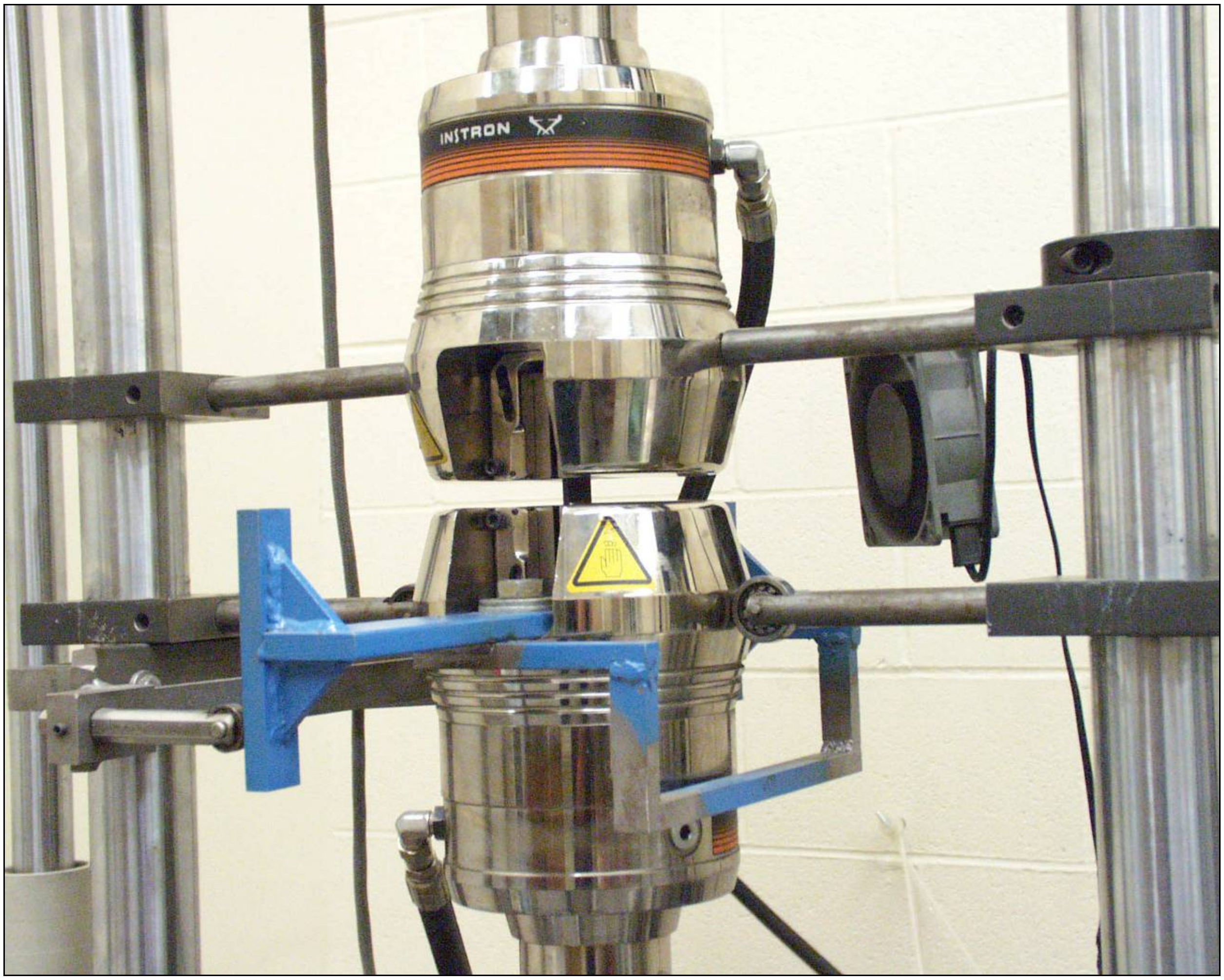
ASTM D3039 Mod. Test Setup at Intec

ASTM D3410 Compression Coupon, Typical

- Thickness varies with laminate
- Length varies with test and gage length
- Gage lengths for testing varied from 6 mm to 18 mm
- Typical load introduction is through shear using a fixture that provides side support
- Primary and secondary dimensions in mm and [in]



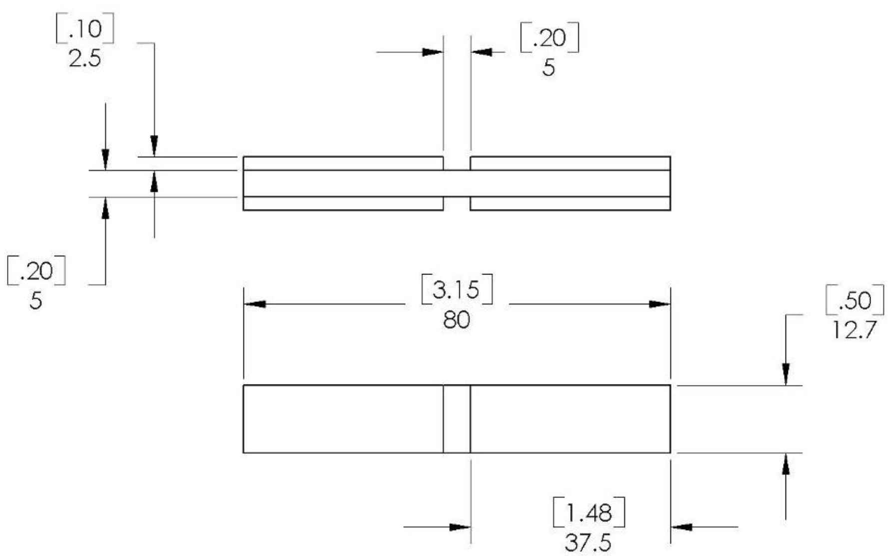


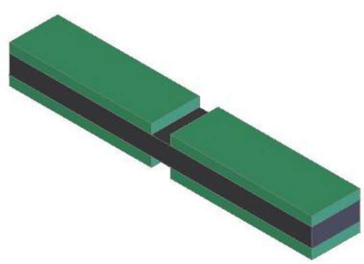


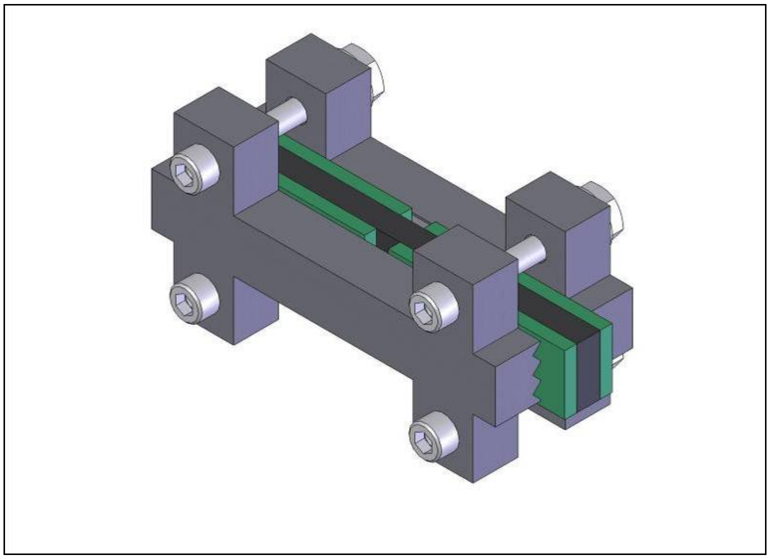
Instron 8501 Grips with Anti Rotation/Translation Supports at MSU (ASTM D3410 Coupon)

ASTM D695 mod. Static Compression Coupon, Typical

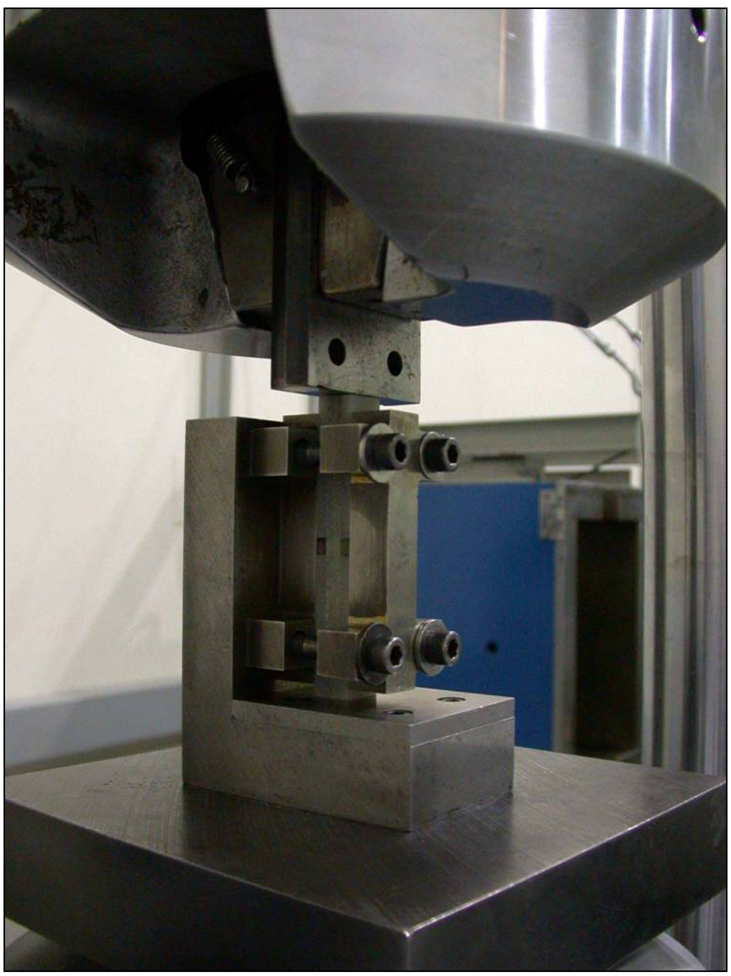
- Thickness varies with laminate
- Modulus coupons not tabbed
- Typical load introduction through ends using a fixture with side support







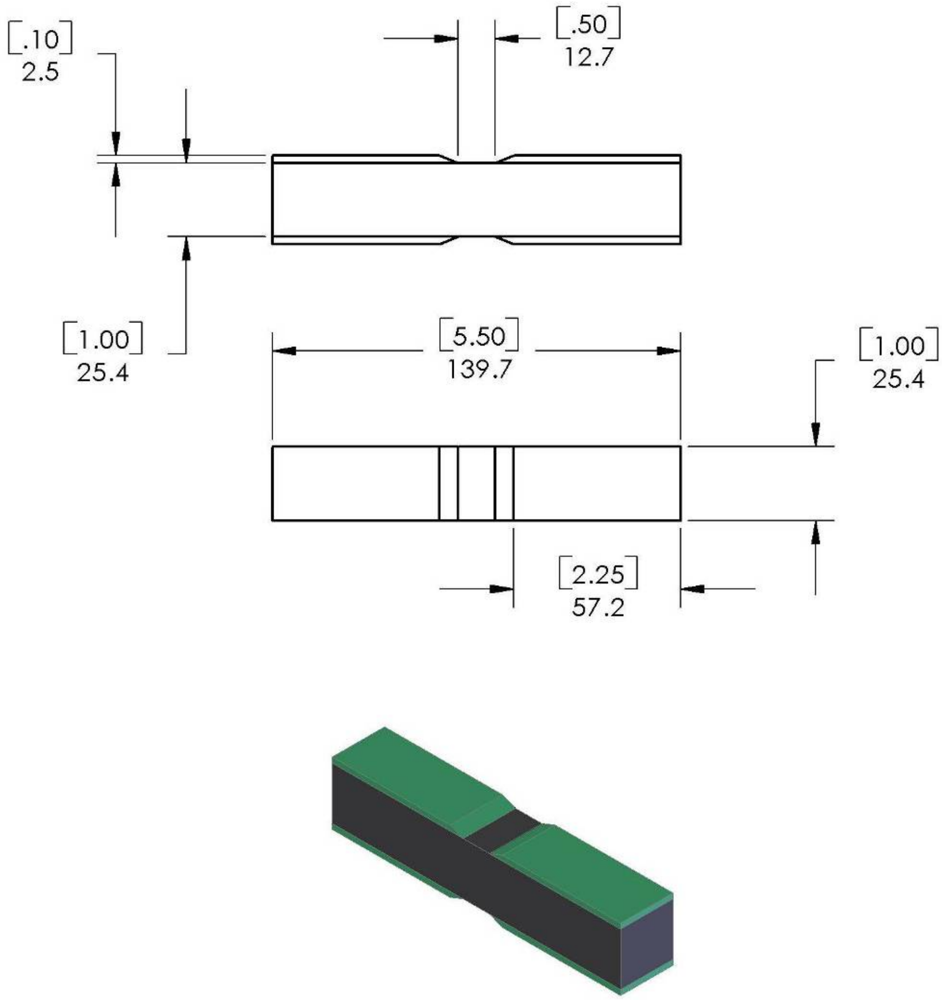
ASTM D695 Mod. Test Fixture



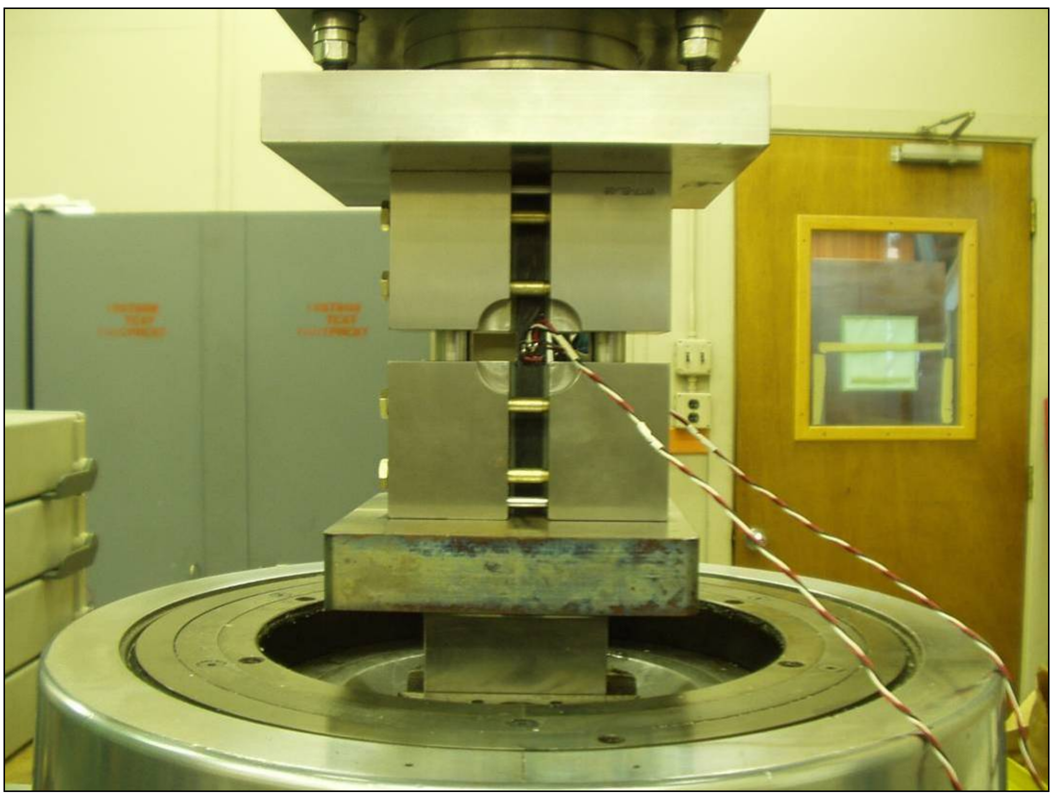
ASTM D695 Mod. Test Setup at Intec

ASTM D6641 Compression Coupon, Typical (Thick)

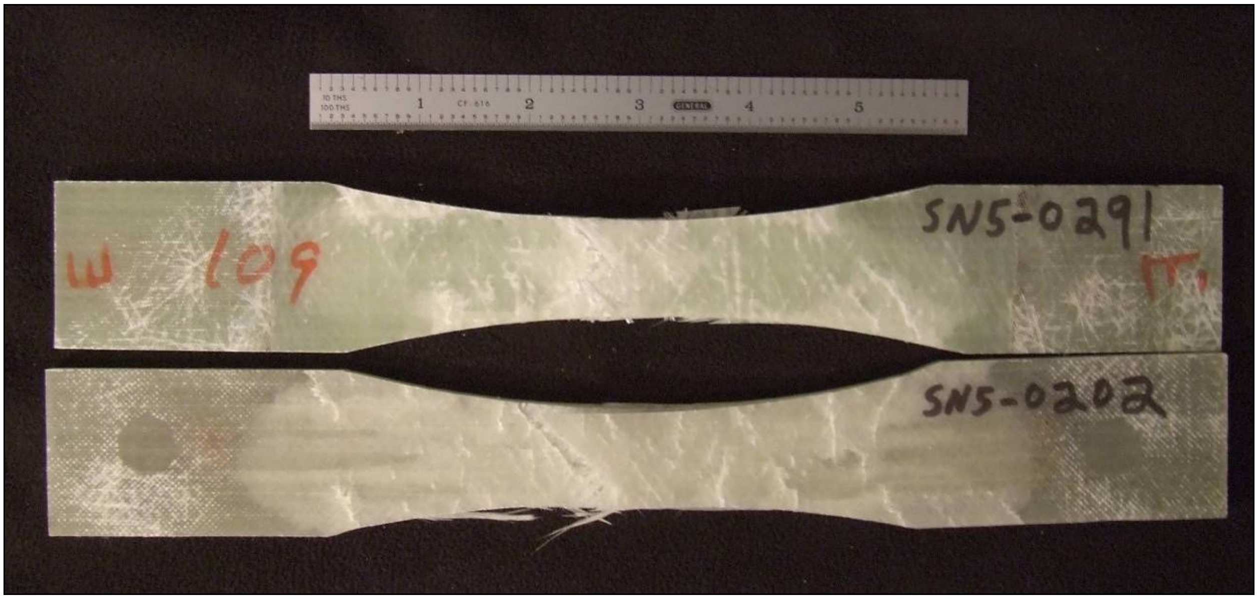
- Thickness varies with laminate (thick coupon shown)
- Width either 12.7 mm or 25.4 mm for tests at WSU
- Typical load introduction is through a fixture which provides combined shear and end loading (CLC)
- Primary and secondary dimensions in mm and [in]



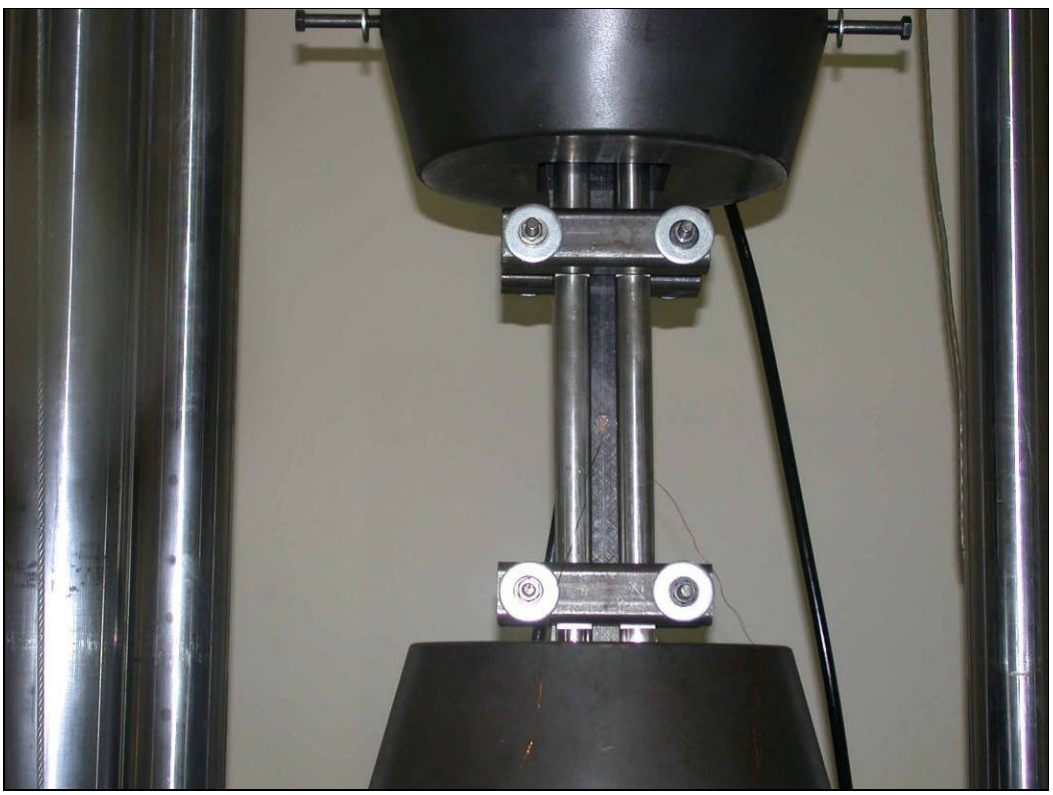
ASTM D6641 Test Fixture at WSU



ASTM D6641 Test Setup at WSU



“Dogbone” Style Thick-Coupons for Testing at Intec

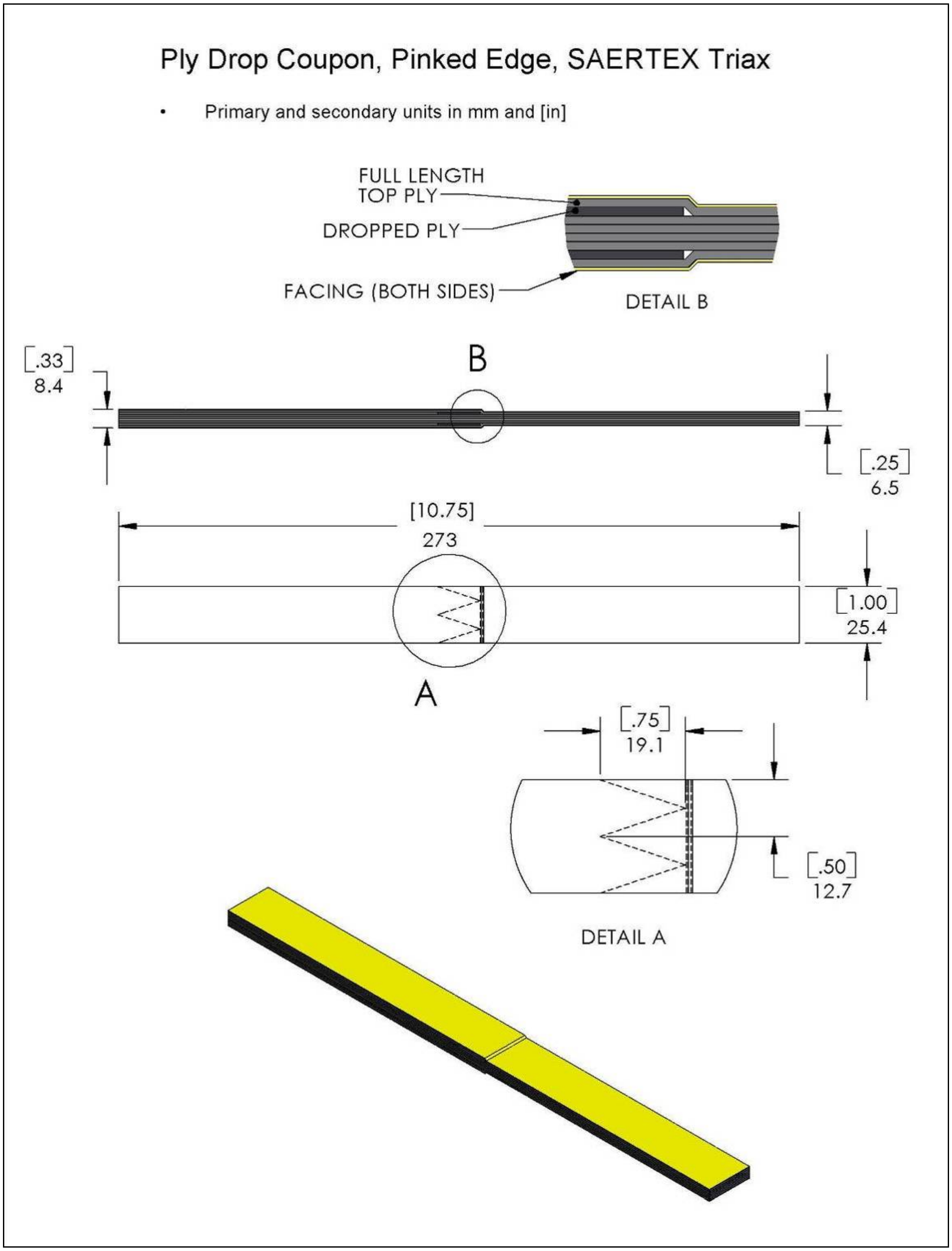


“Dogbone” Style Setup for Thick-Coupon Testing at Intec

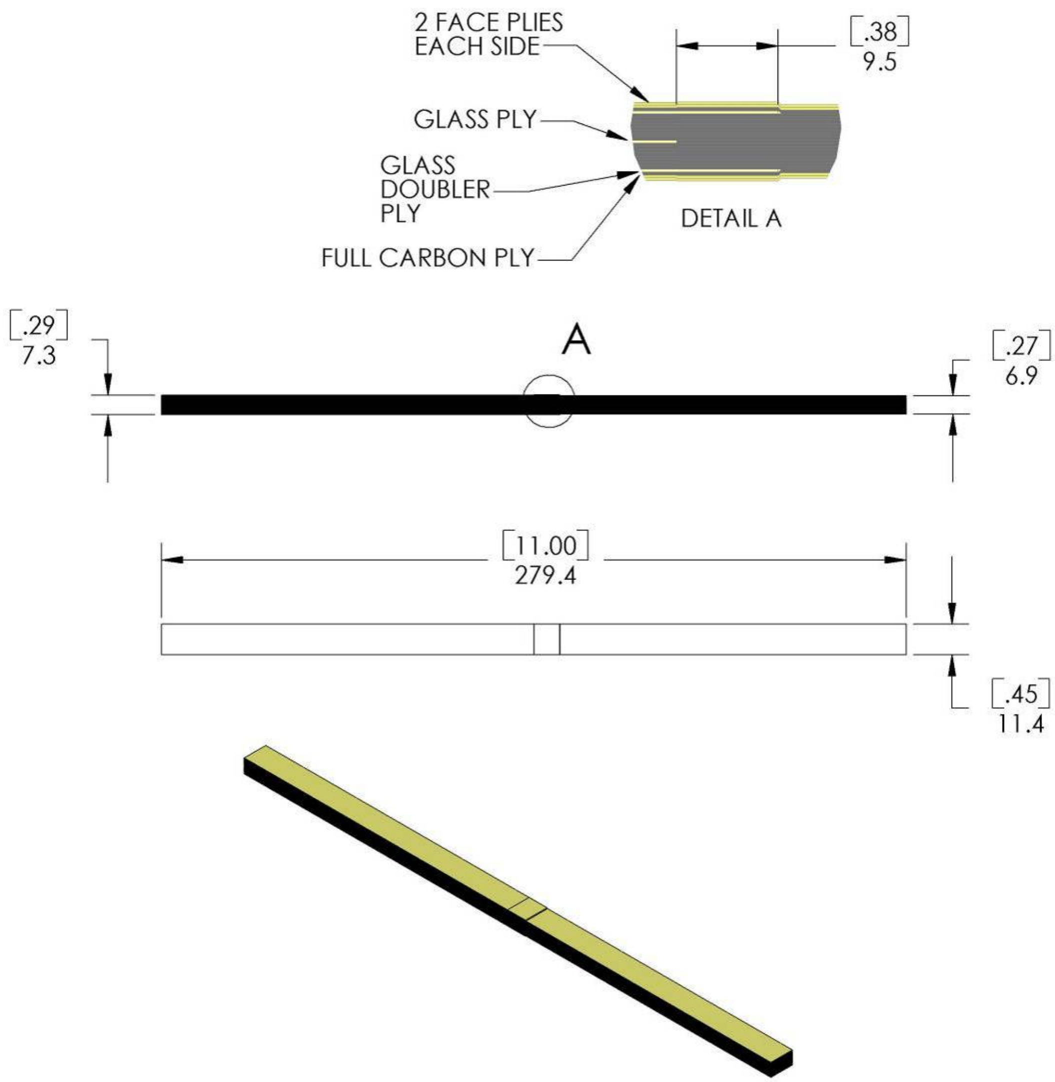
Failure Mode for Dogbone Style Test of Thick-Coupon at Intec

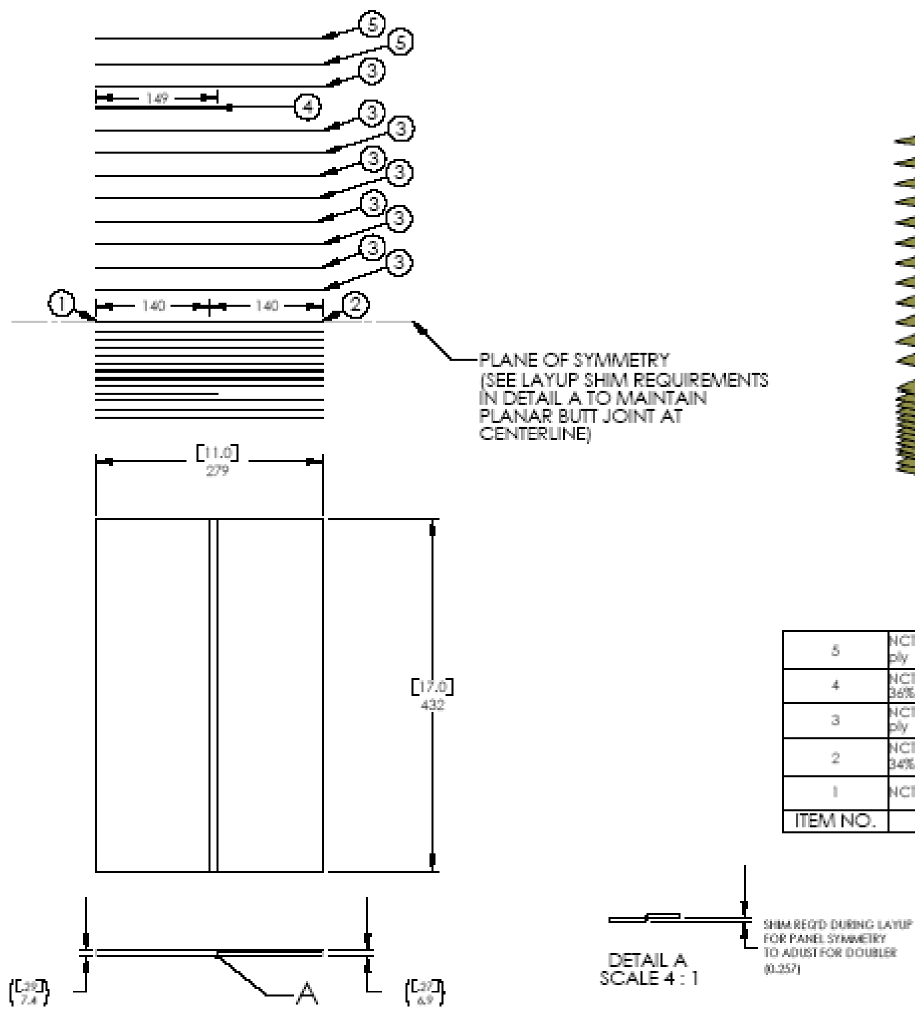
Appendix C

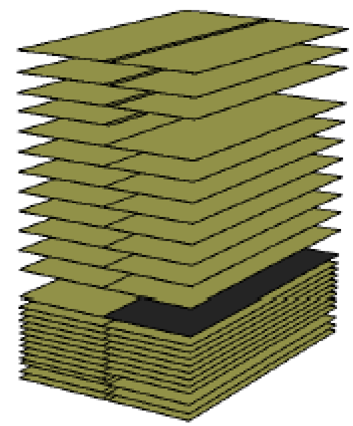
Example Panel Layout Specifications



Transition Coupon, First Carbon Out, Newport Prepreg







ITEM NO.	MATERIAL	PLY ORIENTATION (DEG)	QTY.
5	NCT-307-D1-E300 36%_top ply	+45 (INNER) -45 (OUTER)	4
4	NCT-307-D1-E300 36%_doubler	0	2
3	NCT-307-D1-E300 36%_full ply	0	18
2	NCT-D1-34-700-G300 34%_middle ply1	0	1
1	NCT-307-D1-E300 36%	0	1

	NAME	DATE
DRAWN	DRoberts	10/27/05
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

UNLESS OTHERWISE SPECIFIED, PRIMARY DIM MM DUAL DIM INCHES

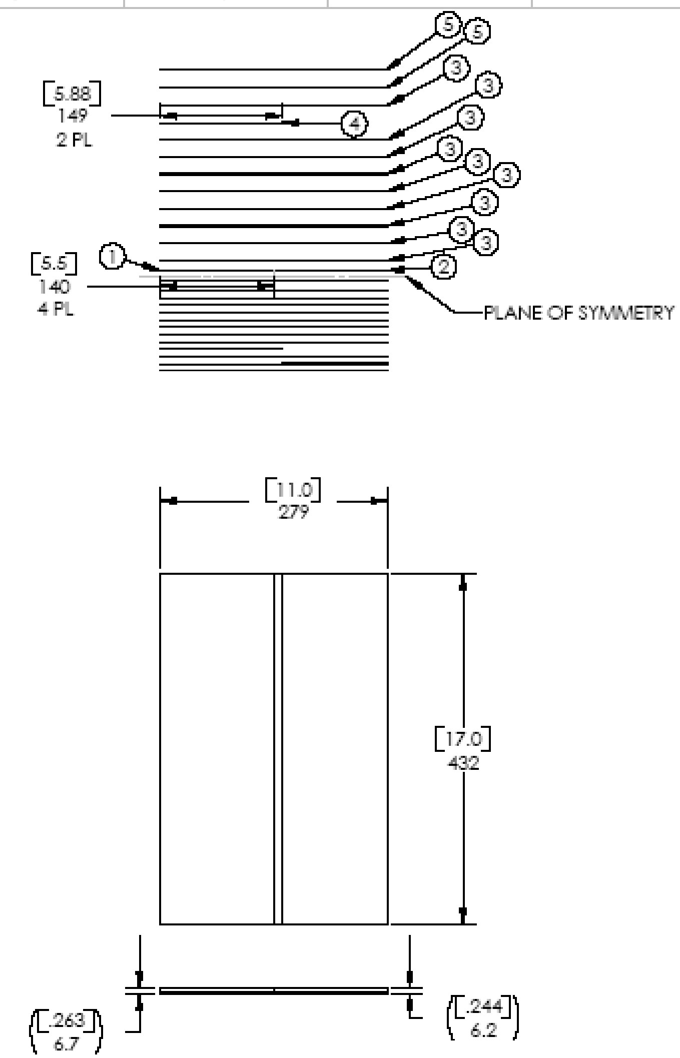
Global Energy Concepts

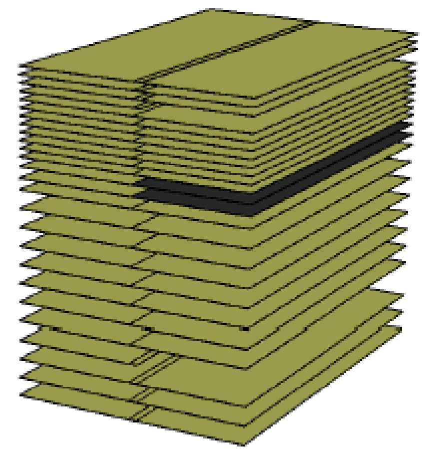
TITLE:

NEWPORT LAST CARBON OUT
1 PLY DROPPED

SIZE B | DWG. NO. Newport Last Carbon Out#2 | REV 0

SCALE: none | WEIGHT: N/A | SHEET 1 OF 1





ITEM NO.	MATERIAL	PLY ORIENTATION	QTY.
5	NCT-307-D1-E300 36% top ply	+/- 45	4
4	NCT-307-D1-E300 36% doubler	0	2
3	NCT-307-D1-E300 36% full ply	0	18
2	NCT-D1-34-700-G300 34%_middle ply	0	2
1	NCT-307-D1-E300 36%	0	2

	NAME	DATE
DRAWN	DRoberts	10/27/05
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

UNLESS OTHERWISE SPECIFIED, PRIMARY DIM MM DUAL DIM INCHES

Global Energy Concepts

TITLE:

NEWPORT LAST CARBON OUT
2 PLIES DROPPED

SIZE: B | DWG. NO.: Newport Last Carbon Out_as built | REV: 0

SCALE: none | WEIGHT: N/A | SHEET 1 OF 1

Appendix D

Tabular Data for Static Tests (Intec)

Data from Intec testing were generally received as reports in PDF format. The following pages contain excerpts from these reports that provide details of the measurements. The report excerpts correspond to panels and static test data as summarized in Table 5-2 and Table 5-5. The Intec reports are generally organized in the same order as the above-referenced tables. The exception to this ordering is in cases where more than one panel is included in a single Intec report page. The GEC panel I.D. number should be used to match the detailed Intec report excerpts to the data summaries in the report tables.

For each panel, the typical order of data in these report excerpts is as follows:

1. Tensile strength and modulus
2. Compressive strength
3. Compressive modulus
4. Resin digestion (including fiber volume fraction, density and void content)
5. Glass transition temperature

Density tests for neat resin samples are at the end of the appendix.

Note that the Intec measurements were made and reported in U.S. units. Data were converted to S.I. units for the tabular summaries presented in the body of this report.

Tension Strength and Modulus
@ Room Temperature

Report Number: 2196-R03
Test Specification: ASTM D3039-00
Purchase Order: Sandria5-1

Crosshead Speed: 0.05 in/min
Test Frame: H
Technician: Nunez

‡Axial Strain @ Ult = ultimate tensile strength / chord modulus
*Ultimate Tensile Strength = ultimate load / (ave width x ave thickness)
‡‡Chord Modulus = delta stress / delta strain
‡‡ Modulus calculated between 1000 & 3000 µs

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	*UltimateTensile Strength *(ksi)*	‡Axial Strain @ Ult *(µε)*	‡‡Chord Modulus *(Msi)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2196-0102	Panel 3	0.999	0.088	25.69	290.8	14,947	19.46	71°F	42%	1/28/2004	Explosive failure in gage section
2196-0103		0.999	0.087	23.68	271.7	14,344	18.94	71°F	42%	1/28/2004	Explosive failure in gage section
2196-0104		0.999	0.087	24.87	287.4	14,481	19.85	71°F	42%	1/28/2004	Explosive failure in gage section
2196-0105		1.000	0.089	24.54	277.1	14,833	18.68	71°F	42%	1/28/2004	Explosive failure in gage section
2196-0106		1.000	0.090	26.15	290.9	15,302	19.01	71°F	42%	1/28/2004	Explosive failure in gage section
				Average:	**283.6**	**14,781**	**19.19**				
				Standard Deviation:	8.7	382	0.46				
				COV:	3.1%	2.6%	2.4%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.
‡Axial strain @ ultimate is calculated due to the extensometer shifting just prior to failure.

Note: “Panel 3” in this report corresponds to GEC Panel ID 013X.

Compression Strength and Modulus
0.75 Inch Gage Section

Report Number: 2196-R04
Test Specification: ASTM D3410-03 Modified
Purchase Order: Sandria5-1

Crosshead Speed: 0.05 in/min
Test Frame: H
Technician: McConnell

*Compression Strength = ultimate load / (ave width x ave thickness)
†%Bending @2000με = ((strain gage 1 - strain gage 2) / (strain gage 1 + strain gage 2)) x 100%
‡Chord Modulus = delta stress / delta strain
‡Modulus calculated between 1000 & 3000 με
††Calculated Axial Strain @ Ult = compression strength / chord modulus

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	*Compression Strength *(ksi)*	†% Bending @2000με *(%)*	‡Chord Modulus *(Msi)*	Axial Strain @ Ult Measured *(με)*	Axial Strain @ Ult ††Calculated *(με)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2196-0201	Panel 3	0.750	0.096	7.23	100.0	1.04%	17.71	5,787	5,650	71°F	35%	2/6/2004	Compressive failure in gage section
2196-0202		0.750	0.095	6.83	95.5	NA	16.81	6,021	5,681	71°F	35%	2/6/2004	Compressive failure in gage section
2196-0203		0.750	0.094	6.95	98.2	NA	15.96	6,592	6,153	71°F	35%	2/6/2004	Compressive failure in gage section
2196-0204		0.750	0.095	7.29	101.8	NA	15.70	7,316	6,485	71°F	35%	2/6/2004	Compressive failure in gage section
2196-0205		0.750	0.094	7.19	101.5	NA	16.07	7,267	6,318	71°F	35%	2/6/2004	Compressive failure in gage section
				Average:	**99.4**		**16.45**	**6,597**	**6,058**				
				Standard Deviation:	2.6		0.81	699	377				
				COV:	2.6%		4.9%	10.6%	6.2%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Notes: "Panel 3" in this report corresponds to GEC Panel ID 013X.
Compressive measurements from these ASTM 3410 tests used, but strength data reported from ASTM D695 tests.

Compression Strength
Modified ASTM D695

Report Number: 2196-R06
Test Specification: ASTM D695-02 Modified
Purchase Order: Sandria5-1

Crosshead Speed: 0.05 in/min
Test Frame: H
Technician: Northrop

††Axial Strain @ Ult for Panel 4 calculated from 0.5" Gage Section Nominal Modulus: 14.6 Msi
††Axial Strain @ Ult for Panel 3 calculated from 0.75" Gage Section Nominal Modulus: 16.5 Msi

*Compression Strength = ultimate load / (ave width x ave thickness)
††Axial Strain @ Ult = compression strength / nominal chord modulus

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	*Compression Strength *(ksi)*	††Axial Strain @ Ult *(με)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2196-0401	Panel 4 SN5-0142	0.502	0.106	9.56	178.9	12,218	74°F	33%	4/5/2004	End failure
2196-0402		0.502	0.113	10.21	179.4	12,257	74°F	33%	4/5/2004	End failure
2196-0403		0.502	0.114	9.05	158.2	10,806	71°F	36%	4/7/2004	Brooming gage / Through thickness at end
2196-0404		0.502	0.115	9.53	164.6	11,241	71°F	36%	4/7/2004	Brooming gage / Through thickness at end
2196-0405		0.501	0.117	8.40	143.7	9,814	71°F	36%	4/7/2004	Brooming gage
2196-0406		0.502	0.114	9.04	157.7	10,772	71°F	36%	4/7/2004	Brooming gage / Through thickness at end
				Average:	**163.7**	**11,184**				
				Standard Deviation:	13.8	940				
				COV:	8.4%	8.4%				
2196-0501	Panel 3	0.502	0.087	7.27	167.2	10,164	73°F	47%	5/11/2004	Delamination / end failure
2196-0502		0.501	0.088	7.53	170.3	10,355	73°F	47%	5/11/2004	Delamination / failure in tab
2196-0503		0.501	0.089	7.77	175.1	10,644	73°F	47%	5/11/2004	Compressive failure at tab
2196-0504		0.502	0.090	8.26	183.9	11,177	73°F	47%	5/11/2004	Compressive failure at tab
2196-0505		0.502	0.088	7.56	170.5	10,365	73°F	47%	5/11/2004	Compressive failure at tab
2196-0506		0.502	0.088	7.31	165.1	10,038	73°F	47%	5/11/2004	Delamination / compressive failure at tab
				Average:	**172.0**	**10,457**				
				Standard Deviation:	6.7	408				
				COV:	3.9%	3.9%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Note: “Panel 3” in this report corresponds to GEC Panel ID 013X.

Resin Digestion

Report Number: 2196-R02 Rev A
Purchase Order: Sandia5-1
Specification: ASTM D3171-99/D2734-94
Hotplate: H_2SO_4/H_2O_2

Fiber Density (g/cc): 1.790
Resin Density (g/cc): 1.212
Test Technician: Jamie Wavra
Test Date: 2/2/2004
Temperature (°C): 22.0

Fiber Volume & Void Content

Specimen ID	Global Energy Panel ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)	Fiber Volume (%)	Resin Volume (%)	Void Volume* (%)
2196-R1		0.9978	1.527	0.504	0.174	1.523	56	43	1.1
2196-R2	SN5-0134 (Panel 3)	0.9978	1.527	0.505	0.174	1.523	56	42	1.3
2196-R3		0.9978	1.530	0.505	0.175	1.526	56	43	0.8
			Average:	**0.505**	**0.174**	**1.524**	**56**	**43**	**1.0**
			Standard Deviation:	0.001	0.001	0.002	0	1	0.3
			COV:	0.2%	0.4%	0.1%	0.6%	1.3%	

*Note: A value for "Void Volume" which is less than zero may be considered equal to zero due to the precision of reporting the densities of the fibers and resin.

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Tg by TMA

Report Number: 2196-R01
Purchase Order: Sandria5-1

Test Technician: Jeanette Francis
Test Date: 1/28/2004

Glass Transition Temperature (TMA by Flexure)

intec ID	Global Energy Panel ID	Specimen Height *(mm)*	Specimen Width *(mm)*	Specimen Depth *(mm)*	Support Span *(mm)*	Static Force *(mN)*	Ramp Rate *(°C/min)*	Tg *(°C)*
2196-Tg1	Panel 3	0.57	20.27	2.37	15	300	5	104

Glass transition temperature is determined from the deflection-temperature curve by the method of intersecting tangents.

Note: “Panel 3” in this report corresponds to GEC Panel ID 013X.

Tension Strength and Modulus @ Room Temperature
Panel SN5-0144

Report Number: 2196-R09
Test Specification: ASTM D3039-00
Purchase Order: Sandia5-1

Crosshead Speed: 0.05 in/min
Test Frame: B
Technician: McConnell

‡Calculated Axial Strain @ Ult = ultimate tensile strength / chord modulus
*Ultimate Tensile Strength = ultimate load / (ave width x ave thickness)
‡‡Chord Modulus = $\Delta\sigma / \Delta\varepsilon$
‡‡ Modulus calculated between 1000 & 3000 με

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	*UltimateTensile Strength *(ksi)*	‡Calculated Axial Strain @ Ult *(με)*	‡‡Chord Modulus *(Msi)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2196-0801	Panel 4 SN5-0144	1.001	0.113	26.26	232	14,343	16.2	69°F	47%	9/21/2004	Tensile failure in gage section
2196-0802		1.001	0.111	28.45	256	16,537	15.5	69°F	47%	9/21/2004	Tensile failure in gage section
2196-0803		1.001	0.115	28.46	248	15,863	15.6	69°F	47%	9/21/2004	Tensile failure in gage section
2196-0804		1.001	0.115	28.34	245	16,397	15.0	69°F	47%	9/21/2004	Tensile failure in gage section
2196-0805		1.001	0.114	25.55	224	14,129	15.8	69°F	47%	9/21/2004	Tensile failure in gage section
2196-0806		1.001	0.114	27.18	238	14,716	16.2	69°F	47%	9/21/2004	Tensile failure in gage section
				Average:	**240**	**15,331**	**15.7**				
				Standard Deviation:	12	1,065	0.5				
				COV:	4.9%	6.9%	2.9%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.
‡No measured strain is available @ ultimate.

Compression Modulus
ASTM D695

Report Number: 2196-R08
Test Specification: ASTM D695-02
Purchase Order: Sandia5-1

Crosshead Speed: 0.05 in/min
Test Frame: I
Technician: Onorati

‡Chord Modulus = Δσ / Δε
‡Modulus calculated between 1000 & 3000 με

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Maximum Load *(kips)*	‡Chord Modulus *(Msi)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2196-0701		0.500	0.118	3.22	15.0	86°F	35%	7/19/2004	No failure, test stopped after 3,500με
2196-0702		0.499	0.114	2.92	13.9	86°F	35%	7/19/2004	No failure, test stopped after 3,500με
2196-0703	Panel 4 SN5-0142	0.499	0.115	2.99	14.6	86°F	35%	7/19/2004	No failure, test stopped after 3,500με
2196-0704		0.499	0.114	3.16	15.3	86°F	35%	7/19/2004	No failure, test stopped after 3,500με
2196-0705		0.498	0.117	3.12	14.7	86°F	35%	7/19/2004	No failure, test stopped after 3,500με
				Average:	**14.7**				
				Standard Deviation:	0.5				
				COV:	3.7%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Resin Digestion
Panel SN5-0142

Report Number: 2196-R11
Purchase Order: Sandia5-1
Specification: ASTM D3171-99/D2734-94
Hotplate: H_2SO_4/H_2O_2

Fiber Density (g/cc): 1.910
Resin Density (g/cc): 1.212
Test Technician: Denise Galasso
Test Date: 11/11/2004
Temperature (°C): 20.1

Fiber Volume & Void Content

Specimen ID	Global Energy Panel ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)	Fiber Volume (%)	Resin Volume (%)	Void Volume* (%)
2196-R31	SN5-0142 (Panel 4) Non-Porous Area	0.9982	1.595	0.701	0.261	1.591	57	42	1.4
2196-R32		0.9982	1.593	0.718	0.267	1.589	52	50	-1.4
2196-R33		0.9982	1.602	0.728	0.273	1.598	57	42	1.1
			Average:	**0.716**	**0.267**	**1.593**	**55**	**44**	**0.4**
			Standard Deviation:	0.013	0.006	0.004	3	5	1.6
			COV:	1.9%	2.2%	0.3%	5.6%	10.5%	
2196-R35	SN5-0142 (Panel 4) Porous Area	0.9982	1.574	0.756	0.275	1.570	54	45	1.3
2196-R36		0.9982	1.572	0.759	0.276	1.568	55	43	2.3
2196-R37		0.9982	1.563	0.744	0.268	1.559	53	45	2.0
			Average:	**0.753**	**0.273**	**1.566**	**54**	**44**	**1.9**
			Standard Deviation:	0.008	0.005	0.006	1	1	0.5
			COV:	1.0%	1.7%	0.4%	1.7%	2.8%	

*Note: A value for "Void Volume" which is less than zero may be considered equal to zero due to the precision of reporting the densities of the fibers and resin.

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Tg by TMA
Panel SN5-0142

Report Number: 2196-R12
Purchase Order: Sandia5-1

Test Technician: Jeanette Francis
Test Date: 11/12/2004

Glass Transition Temperature (TMA by Flexure)

intec **ID**	**Global Energy Panel ID**	**Specimen Height** *(mm)*	**Specimen Width** *(mm)*	**Specimen Depth** *(mm)*	**Support Span** *(mm)*	**Static Force** *(mN)*	**Ramp Rate** *(°C/min)*	**Tg** *(°C)*
2196-T31	SN5-0142 (Panel 4)	0.44	20.16	2.94	15	1000	5	95

Glass transition temperature is determined from the deflection-temperature curve by the method of intersecting tangents.

Tension Strength and Modulus @ Room Temperature

Report Number: 2340-R01
Test Specification: ASTM D3039-00
Purchase Order: Sandia5-4

Crosshead Speed: 0.05 in/min
Test Frame: B
Technician: McConnell

‡Calculated Axial Strain @ Ult = ultimate tensile strength / chord modulus
*Ultimate Tensile Strength = ultimate load / (ave width x ave thickness)
‡‡Chord Modulus = $\Delta\sigma$ / $\Delta\varepsilon$
‡‡ Modulus calculated between 1000 & 3000 $\mu\varepsilon$

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	*UltimateTensile Strength *(ksi)*	‡Calculated Axial Strain @ Ult *($\mu\varepsilon$)*	‡‡Chord Modulus *(Msi)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2340-0301	SN5-0162 (PID 7194)	0.998	0.103	29.04	284	17,314	16.4	71°F	56%	9/22/2004	Combined explosive and angled failure
2340-0302		0.999	0.104	29.29	283	17,010	16.6	71°F	56%	9/22/2004	Combined explosive and angled failure
2340-0303		1.000	0.105	30.18	286	17,431	16.4	71°F	56%	9/22/2004	Combined explosive and angled failure
2340-0304		0.999	0.105	28.74	274	17,355	15.8	71°F	56%	9/22/2004	Combined explosive and angled failure
2340-0305		0.999	0.105	30.26	287	17,280	16.6	71°F	56%	9/22/2004	Combined explosive and angled failure
				Average:	**283**	**17,278**	**16.4**				
				Standard Deviation:	5	160	0.4				
				COV:	1.9%	0.9%	2.2%				
2340-0801	SN5-0182 (7449 Zoltec)	1.001	0.113	25.44	225	14,193	15.8	73°F	43%	9/21/2004	Combined explosive and angled failure
2340-0802		1.000	0.119	25.23	212	13,579	15.6	73°F	43%	9/21/2004	Combined explosive and angled failure
2340-0803		1.000	0.123	23.18	188	12,406	15.2	73°F	43%	9/21/2004	Combined explosive and angled failure
2340-0804		1.000	0.126	24.67	196	12,930	15.2	73°F	43%	9/21/2004	Combined explosive and angled failure
2340-0805		1.000	0.128	24.73	193	12,670	15.3	73°F	43%	9/21/2004	Combined explosive and angled failure
				Average:	**203**	**13,155**	**15.4**				
				Standard Deviation:	15	725	0.3				
				COV:	7.4%	5.5%	1.9%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.
‡No measured strain is available @ ultimate.

Compression Modulus
ASTM D695

Report Number: 2340-R07
Test Specification: ASTM D695-02
Purchase Order: Sandia5-4

Crosshead Speed: 0.05 in/min
Test Frame: B
Technician: Chu

‡Chord Modulus = Δσ / Δε
‡Modulus calculated between 1000 & 3000 με

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Maximum Load *(kips)*	‡Chord Modulus *(Msi)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2340-0321	SN5-0162 (PID 7194)	0.499	0.106	3.03	15.2	73°F	62%	9/28/2004	No failure, test stopped after 3,500με
2340-0322		0.500	0.107	3.16	16.0	73°F	62%	9/28/2004	No failure, test stopped after 3,500με
2340-0323		0.499	0.106	3.26	16.9	73°F	62%	9/28/2004	No failure, test stopped after 3,500με
				Average:	**16.0**				
				Standard Deviation:	0.8				
				COV:	5.1%				
2340-0821	SN5-0182 (7449 Zoltec)	0.501	0.127	3.36	14.0	73°F	62%	9/28/2004	No failure, test stopped after 3,500με
2340-0822		0.501	0.127	3.32	14.0	73°F	62%	9/28/2004	No failure, test stopped after 3,500με
2340-0823		0.501	0.128	3.33	13.9	73°F	62%	9/28/2004	No failure, test stopped after 3,500με
				Average:	**13.9**				
				Standard Deviation:	0.1				
				COV:	0.6%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Resin Digestion
Panel SN5-0162

Report Number: 2340-R05
Purchase Order: Sandia5-4
Specification: ASTM D3171-99/D2734-94
Hotplate: H_2SO_4/H_2O_2

Fiber Density (g/cc): 1.890
Resin Density (g/cc): 1.212
Test Technician: Denise Galasso
Test Date: 10/12/2004
Temperature (°C): 21.4

Fiber Volume & Void Content

Specimen ID	Global Energy Panel ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)	Fiber Volume (%)	Resin Volume (%)	Void Volume* (%)
2340-R31	SN5-0162	0.9980	1.615	0.758	0.288	1.611	60	39	0.6
2340-R32		0.9980	1.592	0.743	0.276	1.588	59	39	2.0
2340-R35		0.9980	1.600	0.737	0.276	1.596	58	41	1.0
2340-R36		0.9980	1.617	0.753	0.287	1.613	58	42	-0.6
2340-R37		0.9980	1.592	0.739	0.275	1.588	57	42	1.0
			Average:	**0.746**	**0.280**	**1.599**	**59**	**41**	**0.8**
			Standard Deviation:	0.009	0.007	0.012	1	1	0.9
			COV:	1.2%	2.4%	0.8%	1.7%	3.6%	

*Note: A value for "Void Volume" which is less than zero may be considered equal to zero due to the precision of reporting the densities of the fibers and resin.

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Resin Digestion
Panel SN5-0182

Report Number: 2340-R06
Purchase Order: Sandia5-4
Specification: ASTM D3171-99/D2734-94
Hotplate: H_2SO_4/H_2O_2

Fiber Density (g/cc): 1.910
Resin Density (g/cc): 1.212
Test Technician: Denise Galasso
Test Date: 9/22/2004
Temperature (°C): 20.0

Fiber Volume & Void Content

Specimen ID	Global Energy Panel ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)	Fiber Volume (%)	Resin Volume (%)	Void Volume* (%)
2340-R81		0.9982	1.575	0.744	0.271	1.571	53	46	0.9
2340-R82	SN5-0182	0.9982	1.565	0.753	0.271	1.561	50	49	0.2
2340-R83		0.9982	1.570	0.760	0.276	1.566	53	46	1.1
			Average:	**0.752**	**0.273**	**1.566**	**52**	**47**	**0.8**
			Standard Deviation:	0.008	0.003	0.005	1	2	0.5
			COV:	1.1%	0.9%	0.3%	2.8%	4.0%	

*Note: A value for "Void Volume" which is less than zero may be considered equal to zero due to the precision of reporting the densities of the fibers and resin.

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Tg by TMA

Report Number: 2340-R03
Purchase Order: Sandia5-4
Test Specification: 299-947-299 Method 509.1 Modified

Test Technician: Jeanette Francis
Test Date: 9/23/2004

Glass Transition Temperature (TMA by Flexure)

intec ID	Global Energy Panel ID	Specimen Height *(mm)*	Specimen Width *(mm)*	Specimen Depth *(mm)*	Support Span *(mm)*	Static Force *(mN)*	Ramp Rate *(°C/min)*	Tg *(°C)*
2340-T31	SN5-0162	0.41	19.66	2.64	15	900	5	105
2340-T81	SN5-0182	0.42	20.33	3.28	15	900	5	101

Glass transition temperature is determined from the deflection-temperature curve by the method of intersecting tangents.

Compression Strength @ Room Temperature

Report Number: 2418-R01
Test Specification: ASTM D695-02 Modified
Purchase Order: Sandia5-9

Crosshead Speed: 0.05 in/min
Test Frame: B
Technician: Hanson

*Compression Strength = ultimate load / (ave width x ave thickness)

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	*Compression Strength *(ksi)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2418-0201		0.501	0.136	10.54	154.4	67°F	33%	1/5/2004	Brooming failure in gage section
2418-0204		0.501	0.136	10.06	147.9	67°F	33%	1/5/2004	Brooming failure in gage section
2418-0205	SN5-2141B	0.501	0.135	10.14	149.8	67°F	33%	1/5/2004	Brooming failure in gage section
2418-0206		0.501	0.133	9.73	145.7	67°F	33%	1/5/2004	Brooming failure in gage section
2418-0208		0.500	0.129	9.94	154.1	67°F	33%	1/5/2004	Brooming failure in gage section
				Average:	**150.4**				
				Standard Deviation:	3.8				
				COV:	2.5%				
2418-0301		0.501	0.120	10.68	176.8	67°F	33%	1/5/2004	Brooming failure in gage section
2418-0302		0.502	0.120	11.06	183.2	67°F	33%	1/5/2004	Brooming failure in gage section
2418-0306	SN5-2111	0.501	0.120	10.66	177.3	67°F	33%	1/5/2004	Brooming failure in gage section
2418-0310		0.501	0.117	10.69	182.6	67°F	33%	1/5/2004	Brooming failure in gage section
2418-0311		0.501	0.116	10.55	181.5	67°F	33%	1/5/2004	Long splitting failure from gage to end
				Average:	**180.3**				
				Standard Deviation:	3.0				
				COV:	1.7%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Compression Modulus @ Room Temperature

Report Number: 2418-R02
Test Specification: ASTM D695-02
Purchase Order: Sandia5-9

Crosshead Speed: 0.05 in/min
Test Frame: B
Technician: Hanson

‡Chord Modulus = Δσ / Δε
‡Modulus calculated between 1000 & 3000 με

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Maximum Load *(kips)*	‡Chord Modulus *(Msi)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2418-0221	SN5-2141B	0.502	0.127	3.51	15.2	68°F	27%	1/5/2004	No failure, test stopped after 3,500με
2418-0222		0.502	0.128	3.54	15.2	68°F	27%	1/5/2004	No failure, test stopped after 3,500με
2418-0223		0.502	0.128	3.54	15.1	68°F	27%	1/5/2004	No failure, test stopped after 3,500με
2418-0224		0.502	0.128	3.55	15.0	68°F	27%	1/5/2004	No failure, test stopped after 3,500με
2418-0225		0.502	0.127	3.53	15.2	68°F	27%	1/5/2004	No failure, test stopped after 3,500με
				Average:	**15.1**				
				Standard Deviation:	0.1				
				COV:	0.6%				
2418-0321	SN5-2111	0.502	0.127	3.00	16.4	68°F	27%	1/5/2004	No failure, test stopped after 3,500με
2418-0322		0.502	0.127	2.97	16.6	68°F	27%	1/5/2004	No failure, test stopped after 3,500με
2418-0323		0.502	0.127	3.18	15.8	68°F	27%	1/5/2004	No failure, test stopped after 3,500με
2418-0324		0.502	0.127	3.29	15.4	68°F	27%	1/5/2004	No failure, test stopped after 3,500με
2418-0325		0.502	0.126	3.43	15.5	68°F	27%	1/5/2004	No failure, test stopped after 3,500με
				Average:	**16.0**				
				Standard Deviation:	0.5				
				COV:	3.3%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Resin Digestion
Panel SN5-02111

Report Number: 2418-R05
Purchase Order: Sandia5-9
Specification: ASTM D3171-99/D2734-94
Hotplate: H_2SO_4/H_2O_2

Fiber Density (g/cc): 1.950
Resin Density (g/cc): 1.212
Test Technician: Denise Galasso
Test Date: 1/11/2005
Temperature (°C): 20.0

Fiber Volume & Void Content

Specimen ID	Global Energy Panel ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)	Fiber Volume (%)	Resin Volume (%)	Void Volume* (%)
2418-R31		0.9982	1.594	0.725	0.270	1.590	54	44	1.8
2418-R32	SN5-02111	0.9982	1.600	0.729	0.273	1.596	54	46	0.9
2418-R33		0.9982	1.597	0.724	0.270	1.593	54	44	1.5
			Average:	**0.726**	**0.271**	**1.593**	**54**	**45**	**1.4**
			Standard Deviation:	0.003	0.002	0.003	0	1	0.4
			COV:	0.4%	0.6%	0.2%	0.7%	1.9%	

*Note: A value for "Void Volume" which is less than zero may be considered equal to zero due to the precision of reporting the densities of the fibers and resin.

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Resin Digestion
Panel SN5-02141B

Report Number: 2418-R04
Purchase Order: Sandia5-9
Specification: ASTM D3171-99/D2734-94
Hotplate: H_2SO_4/H_2O_2

Fiber Density (g/cc): 1.930
Resin Density (g/cc): 1.212
Test Technician: Denise Galasso
Test Date: 1/11/2005
Temperature (°C): 20.0

Fiber Volume & Void Content

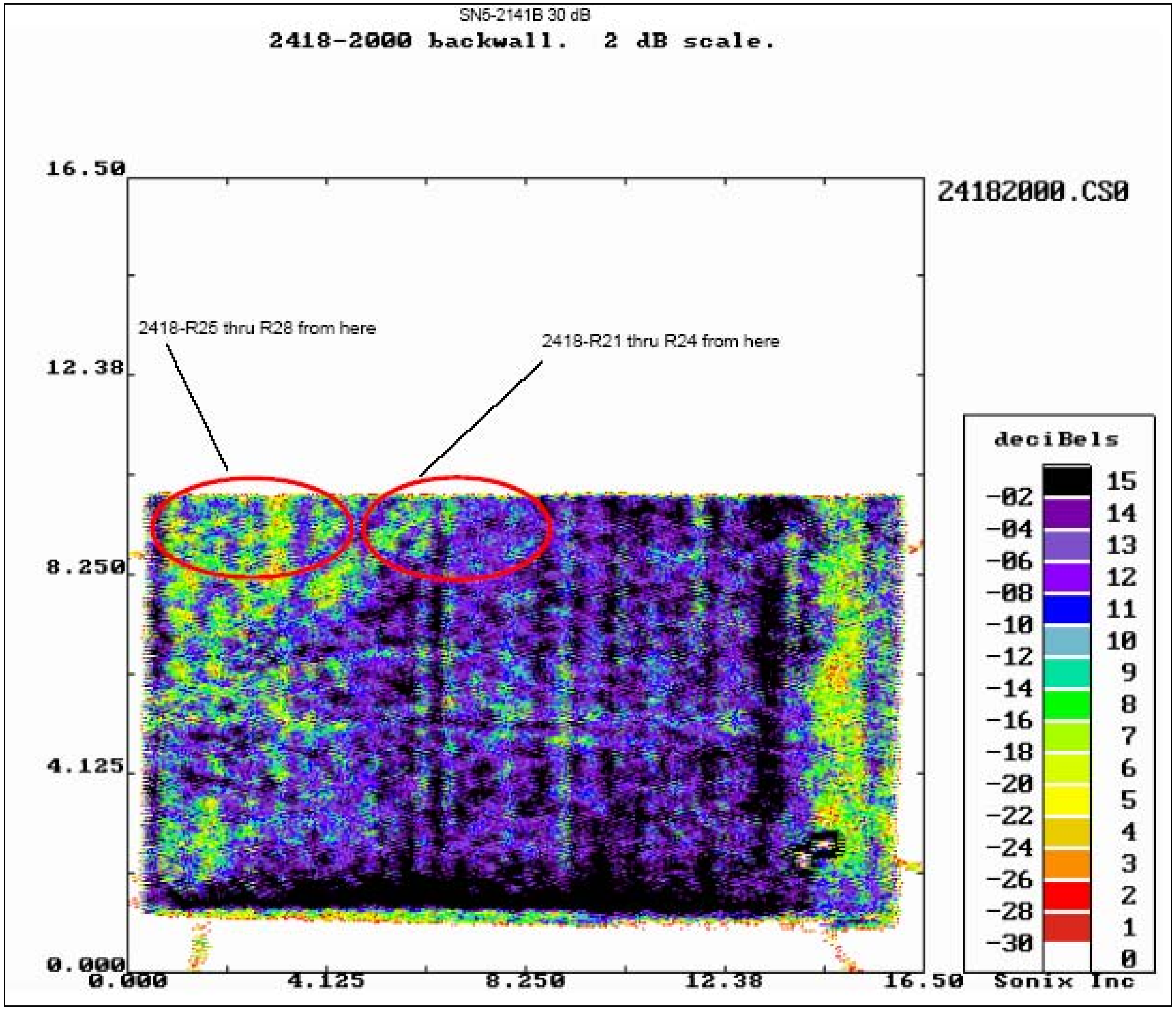
Specimen ID	Global Energy Panel ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)	Fiber Volume (%)	Resin Volume (%)	Void Volume* (%)
2418-R21	SN5-02141B Good Area[1]	0.9982	1.544	0.815	0.287	1.540	48	50	1.6
2418-R22		0.9982	1.539	0.798	0.279	1.535	49	49	2.2
2418-R23		0.9982	1.541	0.810	0.284	1.537	47	52	1.1
			Average:	**0.808**	**0.283**	**1.537**	**48**	**50**	**1.6**
			Standard Deviation:	0.009	0.004	0.003	1	1	0.6
			COV:	1.1%	1.4%	0.2%	1.8%	2.9%	
2418-R25	SN5-02141B Bad Area[1]	0.9982	1.554	0.745	0.266	1.551	51	47	2.1
2418-R26		0.9982	1.549	0.759	0.269	1.545	50	48	2.1
2418-R27		0.9982	1.531	0.775	0.268	1.527	47	51	1.9
			Average:	**0.760**	**0.268**	**1.541**	**49**	**49**	**2.1**
			Standard Deviation:	0.014	0.002	0.012	2	2	0.1
			COV:	1.9%	0.6%	0.8%	3.8%	4.1%	

*Note: A value for "Void Volume" which is less than zero may be considered equal to zero due to the precision of reporting the densities of the fibers and resin.

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

[1] See attached sheet for specimen location.

Note: "Good Area" and "Bad Area" refer to regions of lower and higher porosity per C-Scan inspection (see next page). Strength and modulus data reported were taken from low-porosity ("Good") area of panel SN5-02141B.


SN5-2141B 30 dB
2418-2000 backwall. 2 dB scale.
24182000.CS0
2418-R25 thru R28 from here
2418-R21 thru R24 from here
16.50
12.38
8.250
4.125
0.000
0.000
4.125
8.250
12.38
16.50
deciBels
-02 15
-04 14
-06 13
-08 12
-10 11
-12 10
-14 9
-16 8
-18 7
-20 6
-22 5
-24 4
-26 3
-28 2
-30 1
0
Sonix Inc

Tg by TMA

Report Number: 2418-R03
Purchase Order: Sandia5-9
Test Specification: 299-947-299 Method 509.1 Modified

Test Technician: Jeanette Francis
Test Date: 12/31/2004

Glass Transition Temperature (TMA by Flexure)

intec ID	Global Energy Panel ID	Specimen Height *(mm)*	Specimen Width *(mm)*	Specimen Depth *(mm)*	Support Span *(mm)*	Static Force *(mN)*	Ramp Rate *(°C/min)*	Tg *(°C)*
2418-T21	SN5-2141B	0.49	19.78	3.21	15	700	5	108
2418-T31	SN5-2111	0.50	21.00	2.99	15	800	5	104

Glass transition temperature is determined from the deflection-temperature curve by the method of intersecting tangents.

Tension Strength and Modulus @ Room Temperature

Report Number: 2462-R01
Test Specification: ASTM D3039-00
Purchase Order: Sandia5-13
Extensometer: 80079

Crosshead Speed: 0.05 in/min
Test Frame: B
Technician: Layne

*Ultimate Tensile Strength = ultimate load / (ave width x ave thickness)
‡‡Chord Modulus = $\Delta\sigma$ / $\Delta\varepsilon$
‡‡ Modulus calculated between 1000 & 3000 $\mu\varepsilon$

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	*UltimateTensile Strength *(ksi)*	Axial Strain @ Ult *(με)*	‡Calculated Axial Strain @ Ult *(με)*	Load @ 1 *(lbs)*	Strain @ 1 *(με)*	Load @ 2 *(lbs)*	Strain @ 2 *(με)*	‡‡Chord Modulus *(Msi)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2462-0001	SN5-0311	1.003	0.116	26.76	230.5	14,560	16,051	1,595	1,004	4,923	3,000	14.4	71°F	37%	4/15/2005	Lateral at Tab
2462-0002		1.003	0.118	27.32	231.4	13,410	14,691	1,737	998	5,463	3,002	15.8	71°F	37%	4/15/2005	Lateral at Tab **
2462-0003		1.003	0.118	27.05	229.2	12,620	15,189	1,711	1,000	5,274	3,001	15.1	71°F	37%	4/15/2005	Lateral at Tab
2462-0004		1.003	0.118	26.33	221.8	13,920	15,147	1,647	999	5,128	3,002	14.6	71°F	37%	4/15/2005	Lateral at Tab
2462-0005		1.003	0.118	26.81	226.3	15,488†	15,488	1,764	1,004	5,224	3,003	14.6	71°F	37%	4/15/2005	Lateral at Tab
2462-0006		1.003	0.117	26.64	226.2	13,340	14,583	1,777	1,001	5,427	2,999	15.5	71°F	37%	4/15/2005	Lateral at Tab
				Average:	**227.6**	**13,570**	**15,313**					**15.0**				
				Standard Deviation:	3.5	722	501					0.6				
				COV:	1.6%	5.3%	3.3%					3.7%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.
† Provided calculated value due to extensometer slippage. Calculated Ultimate Axial Strain = (Ultimate Tensile Strength / Chord Modulus) * 1000. Not included in statistics calculations
** Specimen loaded once to 20 kip, unloaded, and retested to failure.

Compression Strength @ Room Temperature

Report Number: 2462-R01
Test Specification: ASTM D695-02 Modified
Purchase Order: Sandia5-13

Crosshead Speed: 0.05 in/min
Test Frame: L
Technician: McConnell
Adhesive: FM300-2

*Compression Strength = ultimate load / (ave width x ave thickness)

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	Fixture Torque *(in-lbs)*	*Compression Strength *(ksi)*	††Axial Strain @ Ult *(με)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2462-0025	SN5-0311	0.501	0.117	10.93	12	186.0	13,376	72°F	36%	4/28/2005	Lateral failure inside tab. (unacceptable) †
2462-0026		0.501	0.118	11.05	35	186.9	13,447	72°F	36%	4/28/2005	Brooming failure in gage section
2462-0027		0.502	0.119	11.21	35	188.3	13,547	72°F	36%	4/28/2005	Brooming failure in gage section
2462-0028		0.501	0.119	11.60	40	194.4	13,982	72°F	36%	4/28/2005	Brooming failure in gage section
2462-0029		0.501	0.119	12.20	40	204.4	14,701	72°F	36%	4/28/2005	Lateral failure inside tab. (unacceptable) †
2462-0030		0.502	0.115	12.41	35	215.9	15,532	72°F	36%	4/28/2005	End failure (unacceptable) †
			Average:	**11.57**		**196.0**	**14097**				
			Standard Deviation:	0.62		11.9	858				
			COV:	5.3%		6.1%	6.1%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

† Though these failure modes are unacceptable according to the spec, the very high loads produced by the laminate are not well suited to the test type. Data should be considered a "minimum strength" for these specimens. All specimens are included in the statistics.

†† Strain calculations were performed using the average chord modulus calculated during the D695 Compression modulus testing. Axial strain = Compression Strength / Chord Modulus

Compression Modulus
ASTM D695

Report Number: 2462-R01
Test Specification: ASTM D695-02
Purchase Order: Sandia5-13

Crosshead Speed: 0.05 in/min
Test Frame: H
Technician: McConnell

These are optional

‡Chord Modulus = Δσ / Δε
‡Modulus calculated between 1000 & 3000 με

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Maximum Load* *(kips)*	Load @ 1 *(lbs)*	Strain @ 1 *(με)*	Load @ 2 *(lbs)*	Strain @ 2 *(με)*	‡Chord Modulus *(Msi)*	Test Temp	Relative Humidity	Test Date	Comments*
2462-0013	SN5-0311	0.502	0.117	2.98	935	990	2,549	2,994	13.7	70°F	40%	4/18/2005	No failure, test stopped after 3,500με
2462-0014		0.503	0.118	3.05	975	1,000	2,640	3,010	14.0	70°F	40%	4/18/2005	No failure, test stopped after 3,500με
2462-0015		0.503	0.118	3.02	986	995	2,607	2,999	13.6	70°F	40%	4/18/2005	No failure, test stopped after 3,500με
2462-0016		0.503	0.118	3.06	1,023	1,016	2,654	2,988	13.9	70°F	40%	4/18/2005	No failure, test stopped after 3,500με
2462-0017		0.503	0.119	3.13	998	999	2,716	3,007	14.3	70°F	40%	4/18/2005	No failure, test stopped after 3,500με
				Average:					**13.9**				
				Standard Deviation:					0.3				
				COV:					1.9%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Resin Digestion
Panel 2262004A

Report Number: 2462-R01
Purchase Order: Sandia5-13
Specification: ASTM D3171-99
Hotplate: H_2SO_4/H_2O_2

†Fiber Density (g/cc): 1.910
‡Resin Density (g/cc): 1.250
Test Technician: Denise Galasso
Test Date: 4/18/2005
Temperature (°C): 20.0

Fiber Volume & Void Content

Specimen ID	Global Energy Panel ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)	Fiber Volume (%)	Resin Volume (%)	Void Volume* (%)
2462-0019	SN5-0311	0.9982	1.589	0.7503	0.2778	1.585	53	46	1.0
2462-0020		0.9982	1.588	0.7223	0.2671	1.584	53	46	1.0
2462-0021		0.9982	1.576	0.7626	0.2784	1.572	51	47	1.3
			Average:	**0.745**	**0.274**	**1.581**	**52**	**47**	**1.1**
			Standard Deviation:	0.021	0.006	0.007	1	1	0.2
			COV:	2.8%	2.3%	0.5%	1.5%	1.3%	

*Note: A value for "Void Volume" which is less than zero may be considered equal to zero due to the precision of reporting the densities of the fibers and resin.

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

†Fiber density is supplied by Global Energy and is assumed to be a weighted average of the glass and carbon fiber densities. This weighted average assumes a constant glass/carbon fiber ratio.

‡Resin density supplied by Global Energy.

Tg by TMA

Report Number: 2462-R01
Purchase Order: Sandia5-13
Test Specification: Tg by TMA

Test Technician: Jeanette Francis
Test Date: 4/21/2005

Glass Transition Temperature (TMA by Flexure)

intec ID	Global Energy Panel ID	Specimen Height *(mm)*	Specimen Width *(mm)*	Specimen Depth *(mm)*	Support Span *(mm)*	Static Force *(mN)*	Ramp Rate *(°C/min)*	Tg *(°C)*
2462-0023	SN5-0311	0.58	20.10	2.85	15	100	5	134

Glass transition temperature is determined from the deflection-temperature curve by the method of intersecting tangents.
Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Tension Strength and Modulus
@ Room Temperature

Report Number: 2220-R01
Test Specification: ASTM D3039-00
Purchase Order: Sandria5-2

Crosshead Speed: 0.05 in/min
Test Frame: B
Technician: Northrop

‡Axial Strain @ Ult = ultimate tensile strength / chord modulus
*Ultimate Tensile Strength = ultimate load / (ave width x ave thickness)
‡‡Chord Modulus = delta stress / delta strain
‡‡ Modulus calculated between 1000 & 3000 µs

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	*UltimateTensile Strength *(ksi)*	‡Axial Strain @ Ult *(µε)*	‡‡Chord Modulus *(Msi)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2220-0102		1.002	0.175	30.09	171.9	14,775	11.63	78°F	32%	4/30/2004	Delamination failure
2220-0103		1.002	0.170	29.90	175.7	15,662	11.22	78°F	32%	4/30/2004	Delamination failure
2220-0104	SN5-0221	1.002	0.167	31.91	190.4	16,808	11.33	78°F	32%	4/30/2004	Delamination failure
2220-0105		1.002	0.172	31.08	180.9	17,088	10.59	78°F	32%	4/30/2004	Delamination failure
2220-0106		1.002	0.170	32.41	189.8	16,640	11.41	78°F	32%	4/30/2004	Delamination failure
				Average:	**181.7**	**16,195**	**11.23**				
				Standard Deviation:	8.3	958	0.39				
				COV:	4.6%	5.9%	3.5%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

‡Axial strain @ ultimate is calculated due to the extensometer shifting just prior to failure.

Compression Strength
Modified ASTM D695

Report Number: 2220-R05
Test Specification: ASTM D695-02 Modified
Purchase Order: Sandria5-2

Crosshead Speed: 0.05 in/min
Test Frame: L
Technician: Onorati

~Panel SN5-0221 compressive chord modulus: 10.2 Msi

*Compression Strength = ultimate load / (ave width x ave thickness)
††Calculated Axial Strain @ Ultimate = compression strength / (panel SN5-0221 chord modulus)

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	*Compression Strength *(ksi)*	††Calculated Axial Strain @ Ult *($\mu\varepsilon$)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2220-0201	SN5-0221	0.503	0.169	8.77	103.0	10,111	78°F	40%	5/28/2004	Brooming failure at tab
2220-0202		0.503	0.172	10.03	115.8	11,368	78°F	40%	5/28/2004	Brooming failure in gage section
2220-0203		0.503	0.174	10.20	116.9	11,473	78°F	40%	5/28/2004	Brooming failure in gage section
2220-0204		0.503	0.172	9.70	112.2	11,015	78°F	40%	5/28/2004	Lateral compressive failure in tab
2220-0205		0.502	0.174	9.99	114.5	11,238	78°F	40%	5/28/2004	Brooming failure in gage section
2220-0206		0.504	0.168	9.15	107.8	10,583	78°F	40%	5/28/2004	Brooming failure at tab
				Average:	**111.7**	**10,965**				
				Standard Deviation:	5.3	524				
				COV:	4.8%	4.8%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.
~Panel SN5-0221 compressive chord modulus in calculated in Intec report 2220-R04

Compression Modulus
Modified ASTM D695

Report Number: 2220-R04
Test Specification: ASTM D695-02
Purchase Order: Sandria5-2

Crosshead Speed: 0.05 in/min
Test Frame: L
Technician: Onorati

*Compression Strength = maximum load / (ave width x ave thickness)
‡Chord Modulus = delta stress / delta strain
‡Modulus calculated between 1000 & 3000 $\mu\varepsilon$

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Maximum Load *(kips)*	‡Chord Modulus *(Msi)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2220-0211	SN5-0221	0.504	0.169	2.89	9.80	78°F	37%	6/1/2004	No failure, test stopped after 3,500$\mu\varepsilon$
2220-0212		0.504	0.173	3.18	10.09	78°F	37%	6/1/2004	No failure, test stopped after 3,500$\mu\varepsilon$
2220-0213		0.504	0.170	3.12	10.35	78°F	37%	6/1/2004	No failure, test stopped after 3,500$\mu\varepsilon$
2220-0214		0.505	0.169	2.97	10.08	78°F	37%	6/1/2004	No failure, test stopped after 3,500$\mu\varepsilon$
2220-0215		0.505	0.170	3.24	10.62	78°F	37%	6/1/2004	No failure, test stopped after 3,500$\mu\varepsilon$
				Average:	**10.19**				
				Standard Deviation:	0.31				
				COV:	3.0%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Resin Digestion

Report Number: 2220-R03 Rev A
Purchase Order: Sandia5-2
Specification: ASTM D3171-99/D2734-94
Hotplate: H_2SO_4/H_2O_2

Fiber Density (g/cc): 2.100
Resin Density (g/cc): 1.159
Test Technician: SaraTesfaye
Test Date: 5/11/2004
Temperature (°C): 26.0

Fiber Volume & Void Content

Specimen ID	Global Energy Panel ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)	Fiber Volume (%)	Resin Volume (%)	Void Volume* (%)
2220-R1	SN5-0221	0.9968	1.688	0.755	0.308	1.684	56	45	-0.2
2220-R2		0.9968	1.688	0.757	0.309	1.683	56	45	-0.2
2220-R3		0.9968	1.691	0.759	0.310	1.686	56	45	-0.4
			Average:	**0.757**	**0.309**	**1.685**	**56**	**45**	**-0.3**
			Standard Deviation:	0.002	0.001	0.002	0	0	0.1
			COV:	0.3%	0.4%	0.1%	0.0%	0.3%	

*Note: A value for "Void Volume" which is less than zero may be considered equal to zero due to the precision of reporting the densities of the fibers and resin.

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Tg by TMA

Report Number: 2220-R02
Purchase Order: Sandria5-2

Test Technician: Jeanette Francis
Tes: Date: 4/29/2004

Glass Transition Temperature (TMA by Flexure)

intec ID	Global Energy Panel ID	Specimen Height *(mm)*	Specimen Width *(mm)*	Specimen Depth *(mm)*	Support Span *(mm)*	Static Force *(mN)*	Ramp Rate *(°C/min)*	Tg *(°C)*
2220-T1	SN5-0221	0.56	20.12	4.35	15	1000	5	64

Glass transition temperature is determined from the deflection-temperature curve by the method of intersecting tangents.

Tension Strength and Modulus @ Room Temperature
ASTM D3039

Report Number: 2490-R01
Test Specification: ASTM D3039-00
Purchase Order: Sandia 5-15
Extensometer: 80079

Crosshead Speed: 0.05 in/min
Test Frame: L
Technician: Layne

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	*UltimateTensile Strength *(ksi)*	‡Calculated Axial Strain @ Ult *(με)*	Load @ 1 *(lbs)*	Strain @ 1 *(με)*	Load @ 2 *(lbs)*	Strain @ 2 *(με)*	‡‡Chord Modulus *(Msi)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2490-2001	02171B	1.002	0.169	27.83 **	163.9	14,060	2,024	1,002	5,985	3,003	11.7	75°F	40%	5/12/2005	Splintering Failure
2490-2002		1.001	0.166	28.24	169.9	14,742	1,981	1,003	5,806	3,000	11.5	75°F	40%	5/12/2005	Splintering Failure
2490-2003		1.002	0.169	27.77	164.5	13,599	2,082	1,002	6,163	3,000	12.1	75°F	40%	5/12/2005	Splintering Failure
2490-2004		1.002	0.168	27.92	165.7	13,604	2,022	999	6,132	3,002	12.2	75°F	40%	5/12/2005	Splintering Failure
2490-2005		1.002	0.165	27.29	165.2	13,571	1,998	1,003	6,014	3,000	12.2	75°F	40%	5/12/2005	Splintering Failure
2490-2006		1.001	0.168	27.33	162.9	13,352	1,991	1,002	6,080	3,000	12.2	75°F	40%	5/12/2005	Splintering Failure
				Average:	**165.3**	**13,821**					**12.0**				
				Standard Deviation:	2.4	507					0.3				
				COV:	1.5%	3.7%					2.5%				

Integrated Technologies Inc certifies the above testing was completed in accordance with the listed specification.

*Ultimate Tensile Strength = ultimate load / (ave width x ave thickness)

** Specimen loaded once to 20 kip, unloaded, and retested to failure.

‡ Calculated Axial Strain @ Ult = Ult Tensile Strength / Chord Modulus * 1000

‡‡Chord Modulus = $\Delta\sigma / \Delta\varepsilon$

‡‡ Modulus calculated between 1000 & 3000 με

Note: Intec report references the TPI-assigned panel number “02171B.” Corresponding GEC I.D. is 026X.

Compression Strength

Report Number: 2490-R01
Test Specification: ASTM D695-02 Modified
Purchase Order: Sandia 5-15

Crosshead Speed: 0.05 in/min
Test Frame: B
Technician: Nunez

*Compression Strength = ultimate load / (ave width x ave thickness)

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	Fixture Torque *(in-lbs)*	*Compression Strength *(ksi)*	††Axial Strain @ Ult *(με)*	Test Temp	Relative Humidity	Test Date	Failure Location & Comments
2490-2025	02171B	0.498	0.171	6.60	8	77.7 †	6,754 †	75°F	44%	5/25/2005	End failure
2490-2026		0.497	0.181	8.33	8	92.9 †	8,072 †	75°F	44%	5/25/2005	End failure
2490-2027		0.496	0.178	10.2	35	115	10,024	75°F	44%	5/25/2005	Broom failure in the gage section
2490-2028		0.497	0.179	10.7	35	120	10,426	75°F	44%	5/25/2005	Horizontal failure in the tabs
2490-2029		0.497	0.177	11.1	35	126	10,981	75°F	44%	5/25/2005	Broom failure in the gage section
2490-2030		0.499	0.176	9.21	35	105	9,107	75°F	44%	5/25/2005	Horizontal failure at the tabs
			Average:	**9.34**		**117**	**10,134**				
			Standard Deviation:	1.67		9.1	789				
			COV:	17.9%		7.8%	7.8%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

† Values not included in Average, Stan. Dev, or COV calculations.

†† Strain calculations were performed using the average chord modulus calculated during the D695 Compression modulus testing.
Axial strain = Compression Strength / Chord Modulus

Compression Modulus

Report Number: 2490-R01
Test Specification: ASTM D695-02
Purchase Order: Sandia 5-15

Crosshead Speed: 0.05 in/min
Test Frame: B
Technician: Layne

‡Chord Modulus = Δσ / Δε
‡Modulus calculated between 1000 & 3000 με

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Maximum Load* *(kips)*	Load @ 1 *(lbs)*	Strain @ 1 *(με)*	Load @ 2 *(lbs)*	Strain @ 2 *(με)*	‡Chord Modulus *(Msi)*	Test Temp	Relative Humidity	Test Date	Comments
2490-2013	02171B	0.502	0.166	3.55	1,200	1,008	3,081	2,995	11.4	72°F	46%	5/11/2005	No failure, test stopped after 3,500με
2490-2014		0.502	0.170	3.77	1,208	995	3,268	3,008	12.0	72°F	46%	5/11/2005	No failure, test stopped after 3,500με
2490-2015		0.501	0.170	3.45	1,077	1,002	2,986	3,003	11.2	72°F	46%	5/11/2005	No failure, test stopped after 3,500με
2490-2016		0.502	0.166	3.51	1,093	998	3,040	2,999	11.7	72°F	46%	5/11/2005	No failure, test stopped after 3,500με
2490-2017		0.501	0.172	3.51	1,101	1,000	3,027	2,990	11.2	72°F	46%	5/11/2005	No failure, test stopped after 3,500με
				Average:					**11.5**				
				Standard Deviation:					0.3				
				COV:					3.0%				

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Resin Digestion

Report Number: 2490-R01
Purchase Order: Sandia 5-15
Specification: ASTM D3171-99
Hotplate: H_2SO_4/H_2O_2

†Fiber Density (g/cc): 2.12
‡Resin Density (g/cc): 1.168
Test Technician: Denise Galasso
Test Date: 5/24/05
Temperature (°C): 20.0

Fiber Volume & Void Content

Specimen ID	Global Energy Panel ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)	% Resin by Weight	Fiber Volume (%)	Resin Volume (%)	Void Volume* (%)
2490-2019	02171B	0.9982	1.702	0.7590	0.3127	1.698	29.0	57	42	1.0
2490-2020		0.9982	1.693	0.7847	0.3208	1.689	31.4	55	45	0.0
2490-2022		0.9982	1.697	0.7549	0.3098	1.693	32.6	54	47	-1.1
			Average:	**0.766**	**0.314**	**1.693**	**30.984**	**55**	**45**	**0.0**
			Standard Deviation:	0.016	0.006	0.005	1.851	2	3	1.0
			COV:	2.1%	1.8%	0.3%	6.0%	2.9%	5.8%	-3464.8%

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

*Note: A value for "Void Volume" which is less than zero may be considered equal to zero due to the precision of reporting the densities of the fibers and resin.

†Fiber density is supplied by Global Energy and is assumed to be a weighted average of the glass and carbon fiber densities. This weighted average assumes a constant glass/carbon fiber ratio.

‡Resin density is the result from the neat resin density testing performed for this project.

Tg by TMA

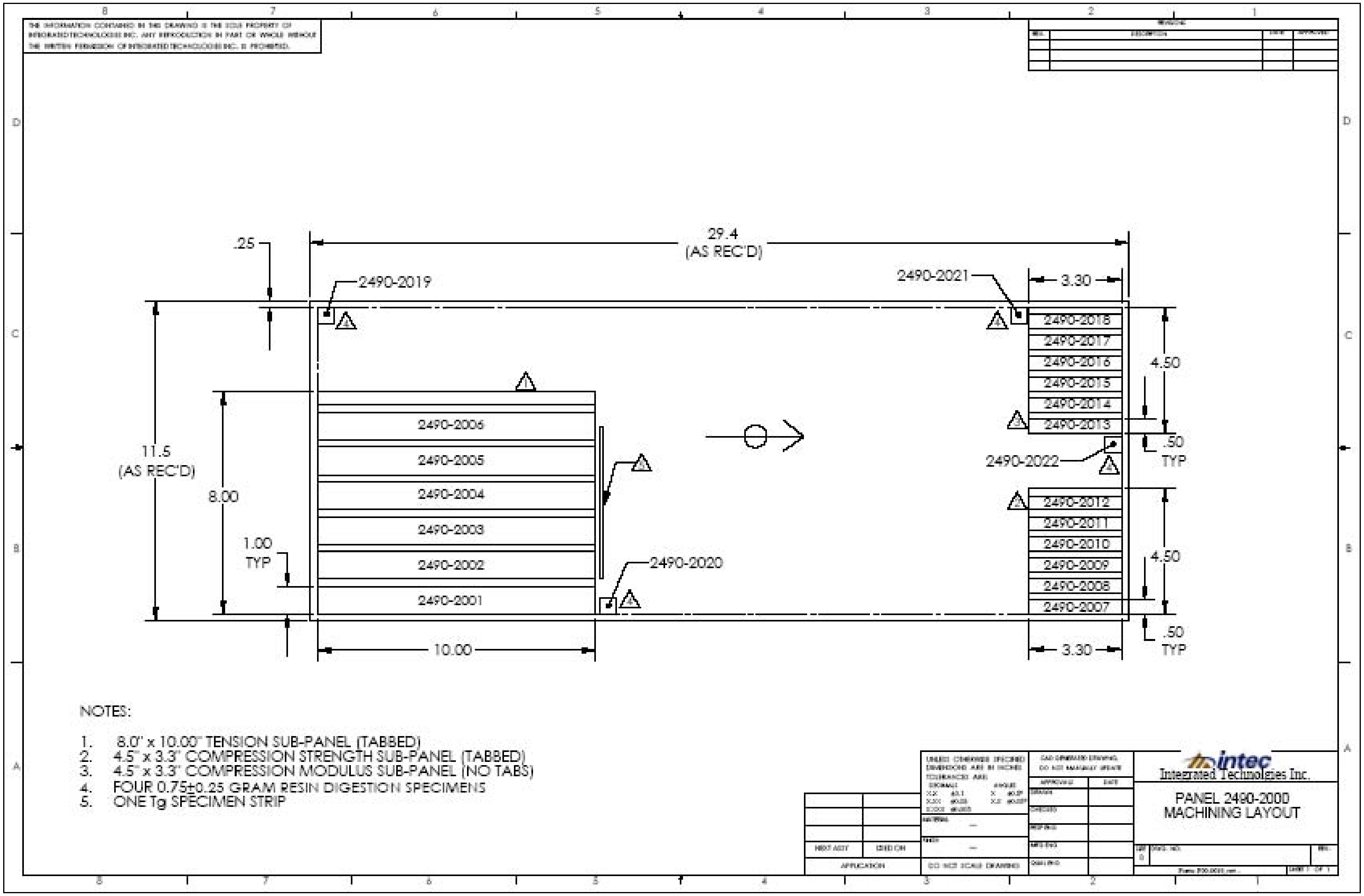
Report Number: 2490-R01
Purchase Order: Sandia 5-15
Test Specification: Tg by TMA

Test Technician: Jeanette Francis
Test Date: 5/12/2005

Glass Transition Temperature (TMA by Flexure)

intec ID	Global Energy Panel ID	Specimen Height *(mm)*	Specimen Width *(mm)*	Specimen Depth *(mm)*	Support Span *(mm)*	Static Force *(mN)*	Ramp Rate *(°C/min)*	Tg *(°C)*
2490-2023	02171B	0.49	19.82	4.31	15	50	5	65

Glass transition temperature is determined from the deflection-temperature curve by the method of intersecting tangents.
Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.



Note: Example of layout for panel machining.

Tension Strength and Modulus @ Room Temperature

Set 2

Report Number: 2691-R01 Appendix C
Test Specification: ASTM D3039-00
GEC Test Plan: GEC-TS025 Rev B
Purchase Order: 1081

Extensometer ID: E80410

Crosshead Speed: 0.05 in/min
Test Frame: L
Technician: McConnell
Test Date: 11/2/2006
Test Temp: 67°F
Test Relative Humidity: 38%

†Ultimate Tensile Strength = ultimate load / (ave width x ave thickness)
‡Calculated Axial Strain @ Ult = ultimate tensile strength / chord modulus
‡‡Chord Modulus = $\Delta\sigma$ / $\Delta\varepsilon$
‡‡ Modulus calculated between 1000 & 3000 $\mu\varepsilon$

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	†Ultimate Tensile Strength *(ksi)*	‡Calculated Axial Strain @ Ult *($\mu\varepsilon$)*	‡‡Chord Modulus *(Msi)*	Failure Location & Comments
2691-2001	SN5-0201	1.000	0.177	18.4	103.7	23,348	4.44	Long splitting failure
2691-2002		1.001	0.180	18.0	99.8	23,558	4.23	Long splitting failure
2691-2003		1.002	0.177	17.9	101.1	22,058	4.59	Long splitting failure
2691-2004		1.001	0.179	18.2	101.4	22,648	4.48	Long splitting failure
2691-2005		1.000	0.177	18.1	102.6	22,747	4.51	Long splitting failure
2691-2006		1.000	0.175	18.8	107.1	23,608	4.54	Long splitting failure
2691-2007		1.000	0.180	18.7	103.6	23,619	4.39	Long splitting failure
2691-2008		1.001	0.179	18.3	102.0	22,142	4.61	Long splitting failure
2691-2009		1.001	0.176	17.9	101.4	22,471	4.51	Long splitting failure
2691-2010		1.001	0.176	18.5	104.6	23,157	4.52	Long splitting failure
2691-2011		1.001	0.178	18.3	102.8	23,036	4.46	Long splitting failure
				Average:	**102.7**	**22,945**	**4.48**	
				Standard Deviation:	2.0	572	0.10	
				COV:	1.9%	2.5%	2.3%	

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.
‡Extensometer was removed just prior to reaching ultimate load. Failure strain reported is calculated.

Compression Strength @ Room Temperature
Set 2

Report Number: 2691-R01 Appendix D
Test Specification: ASTM D695-02 Modified
GEC Test Plan: GEC-TS025 Rev B
Purchase Order: 1081

‡Fixture Torque: 30 in-lbs

Crosshead Speed: 0.05 in/min
Test Frame: L
Technician: McConnell
Test Date: 11/3/2006
Test Temp: 68°F
Test Relative Humidity: 43%

†Ultimate Comp Strength = ultimate load / (ave width x ave thickness)

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	†Ultimate Comp Strength *(ksi)*	Failure Location & Comments
2691-2101	SN5-0201	0.501	0.179	9.2	~102.2	Brooming inside tab. 10 in-lbs of torque used on fixture.
2691-2102		0.502	0.182	9.5	104.1	Brooming in gage section
2691-2103		0.501	0.181	9.9	~109.3	Brooming inside tab
2691-2104		0.502	0.181	10.2	112.6	Brooming in gage section
2691-2105		0.502	0.177	10.0	~112.8	Brooming inside tab
2691-2106		0.502	0.174	9.2	~105.6	Brooming inside tab
2691-2107		0.501	0.176	8.8	99.4	Brooming in gage section
2691-2108		0.501	0.175	9.5	108.3	Brooming in gage section
2691-2109		0.501	0.171	9.7	113.6	Brooming in gage section
2691-2110		0.501	0.168	9.7	115.8	Brooming in gage section
2691-2111		0.501	0.168	9.6	114.2	Brooming in gage section
2691-2112		0.501	0.167	9.3	111.0	Brooming in gage section
				Average:	**109.9**	
				Standard Deviation:	5.6	
				COV:	5.1%	

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.
~Due to unacceptable failure mode, the strength is reported but not included in the group statistics.

Compression Modulus @ Room Temperature
Set 2

Report Number: 2691-R01 Appendix E
Test Specification: ASTM D695-02 Modified
GEC Test Plan: GEC-TS025 Rev B
Purchase Order: 1081

Fixture Torque: 10 in-lbs
Strain Gage Type: CEA-06-125UN-350

Crosshead Speed: 0.05 in/min
Test Frame: L
Technician: McConnell
Test Date: 11/3/2006
Test Temp: 68°F
Test Relative Humidity: 48%

‡‡Chord Modulus = $\Delta\sigma / \Delta\varepsilon$
‡‡ Modulus calculated between 1000 & 3000 $\mu\varepsilon$

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	‡‡Chord Modulus *(Msi)*	Failure Location & Comments
2691-2121	SN5-0201	0.502	0.179	1.6	5.14	Stopped after reaching 3,500με
2691-2122		0.501	0.183	1.6	4.79	Stopped after reaching 3,500με
2691-2123		0.502	0.175	1.6	4.82	Stopped after reaching 3,500με
2691-2124		0.501	0.176	1.5	4.80	Stopped after reaching 3,500με
2691-2125		0.502	0.174	1.6	4.99	Stopped after reaching 3,500με
2691-2126		0.502	0.177	1.8	5.49	Stopped after reaching 3,500με
2691-2127		0.502	0.188	1.8	4.98	Stopped after reaching 3,500με
2691-2128		0.501	0.186	1.8	5.46	Stopped after reaching 3,500με
2691-2129		0.502	0.181	1.7	5.10	Stopped after reaching 3,500με
2691-2130		0.500	0.178	1.7	4.96	Stopped after reaching 3,500με
				Average:	**5.05**	
				Standard Deviation:	0.25	
				COV:	5.0%	

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Resin Digestion
Set 2

Report Number: 2691-R01 Appendix G
Purchase Order: 1081
Specification: ASTM D3171-99/D2734-94
Hotplate: H_2SO_4/H_2O_2
GEC Test Plan: GEC-TS025 Rev B

Fiber Density (g/cc): 2.55
Resin Density (g/cc): 1.17
Test Technician: Jessica Dieter
Test Date: 10/27/2006
Temperature (°C): 21.0

Fiber Volume & Void Content

Specimen ID	Global Energy Panel ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)	Fiber Volume (%)	Resin Volume (%)	Void Volume* (%)
2691-2141	SN5-0201	0.9980	1.950	0.740	0.360	1.945	55	46	-1.2
2691-2142		0.9980	1.974	0.767	0.378	1.970	57	44	-0.9
2691-2143		0.9980	1.963	0.744	0.365	1.958	57	43	-0.3
			Average:	**0.750**	**0.368**	**1.958**	**56**	**44**	**-0.8**
			Standard Deviation:	0.015	0.009	0.012	1	1	0.5
			COV:	2.0%	2.6%	0.6%	1.9%	3.2%	

*Note: A value for "Void Volume" which is less than zero may be considered equal to zero due to the precision of reporting the densities of the fibers and resin.

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Tg by TMA
Set 2

Report Number: 2691-R01 Appendix F
GEC Test Plan: GEC-TS025 Rev B
Purchase Order: 1081

Test Technician: Jeanette Francis
Test Date: 11/2/2006

Glass Transition Temperature (TMA by Flexure)

intec **ID**	**Global Energy Panel ID**	**Specimen Height** *(mm)*	**Specimen Width** *(mm)*	**Specimen Depth** *(mm)*	**Support Span** *(mm)*	**Static Force** *(mN)*	**Ramp Rate** *(°C/min)*	**Tg** *(°C)*	**Tg** *(°F)*
2691-2151	SN5-0201	0.55	20.06	4.34	15	1500	5	104	219

Glass transition temperature is determined from the deflection-temperature curve by the method of intersecting tangents.

Tension Strength and Modulus @ Room Temperature
Set 3

Report Number: 2691-R01 Appendix C
Test Specification: ASTM D3039-00
GEC Test Plan: GEC-TS024 Rev B
Purchase Order: 1081

Extensometer ID: E80410

Crosshead Speed: 0.05 in/min
Test Frame: H
Technician: Wade
Test Date: 12/14/2006
Test Temp: 68°F
Test Relative Humidity: 33%

†Ultimate Tensile Strength = ultimate load / (ave width x ave thickness)
‡Calculated Axial Strain @ Ult = ultimate tensile strength / chord modulus
‡‡Chord Modulus = Δσ / Δε
‡‡ Modulus calculated between 1000 & 3000 με

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	†Ultimate Tensile Strength *(ksi)*	‡Calculated Axial Strain @ Ult *(με)*	‡‡Chord Modulus *(Msi)*	Failure Location & Comments
2691-3001	SN5-0290	1.002	0.178	18.5	104.0	21,658	4.80	Long splitting failure
2691-3002		1.002	0.184	18.6	101.0	21,965	4.60	Long splitting failure
2691-3003		1.003	0.178	18.6	104.1	22,663	4.59	Long splitting failure
2691-3004		1.002	0.184	19.0	103.1	22,349	4.61	Long splitting failure
2691-3005		1.002	0.180	18.3	101.2	22,217	4.55	Long splitting failure
2691-3006		1.002	0.183	18.3	100.1	23,016	4.35	Long splitting failure
2691-3007		1.002	0.189	19.1	101.0	22,125	4.56	Long splitting failure
2691-3008		1.002	0.181	18.5	102.0	23,380	4.36	Long splitting failure
2691-3009		1.003	0.183	18.7	101.5	23,682	4.29	Long splitting failure
2691-3010		1.002	0.182	18.7	102.7	23,356	4.40	Long splitting failure
				Average:	**102.1**	**22,641**	**4.51**	
				Standard Deviation:	1.4	686	0.16	
				COV:	1.3%	3.0%	3.5%	

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.
‡Extensometer was removed just prior to reaching ultimate load. Failure strain reported is calculated.

Compression Strength @ Room Temperature
Set 3

Report Number: 2691-R01 Appendix D
Test Specification: ASTM D695-02 Modified
GEC Test Plan: GEC-TS024 Rev B
Purchase Order: 1081

‡Fixture Torque: 30 in-lbs

Crosshead Speed: 0.05 in/min
Test Frame: I
Technician: Hanson
Test Date: 12/15/2006
Test Temp: 66°F
Test Relative Humidity: 40%

†Ultimate Comp Strength = ultimate load / (ave width x ave thickness)

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	†Ultimate Comp Strength *(ksi)*	Failure Location & Comments
2691-3101	SN5-0290	0.501	0.182	9.1	100.0	Brooming in gage section
2691-3102		0.501	0.179	9.8	109.6	Brooming in gage section
2691-3103		0.502	0.175	9.7	110.4	Brooming in gage section
2691-3104		0.502	0.179	9.5	105.5	Brooming in gage section
2691-3105		0.502	0.188	9.9	105.2	Brooming in gage section
2691-3106		0.502	0.188	9.3	98.3	Brooming in gage section
2691-3107		0.501	0.180	8.9	~98.8	Brooming inside tab
2691-3108		0.501	0.178	9.5	~106.8	Brooming inside tab
2691-3109		0.502	0.175	9.1	104.0	Brooming in gage section
2691-3110		0.502	0.180	8.6	~95.6	Brooming inside tab
2691-3111		0.502	0.178	8.6	95.4	Brooming in gage section
2691-3112		0.502	0.173	7.6	87.2	Brooming in gage section
				Average:	**101.8**	
				Standard Deviation:	7.4	
				COV:	7.2%	

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.
~Due to unacceptable failure mode, the strength is reported but not included in the group statistics.

Compression Modulus @ Room Temperature
Set 3

Report Number: 2691-R01 Appendix E
Test Specification: ASTM D695-02 Modified
GEC Test Plan: GEC-TS024 Rev B
Purchase Order: 1081

Fixture Torque: 10 in-lbs
Strain Gage Type: CEA-06-125UN-350

Crosshead Speed: 0.05 in/min
Test Frame: I
Technician: Hanson
Test Date: 12/14/2006
Test Temp: 67°F
Test Relative Humidity: 29%

‡‡Chord Modulus = $\Delta\sigma / \Delta\varepsilon$
‡‡ Modulus calculated between 1000 & 3000 $\mu\varepsilon$

Intec ID	Global Energy Panel ID	Average Width *(in)*	Average Thickness *(in)*	Ultimate Load *(kips)*	‡‡Chord Modulus *(Msi)*	Failure Location & Comments
2691-3121	SN5-0290	0.501	0.180	1.6	4.51	Stopped after reaching 3,500με
2691-3122		0.501	0.182	1.6	4.56	Stopped after reaching 3,500με
2691-3123		0.501	0.179	1.6	4.63	Stopped after reaching 3,500με
2691-3124		0.501	0.180	1.7	4.71	Stopped after reaching 3,500με
2691-3125		0.501	0.183	1.6	4.57	Stopped after reaching 3,500με
2691-3126		0.502	0.178	1.5	4.43	Stopped after reaching 3,500με
2691-3127		0.501	0.182	1.5	4.38	Stopped after reaching 3,500με
2691-3128		0.502	0.179	1.5	4.38	Stopped after reaching 3,500με
2691-3129		0.502	0.180	1.6	4.70	Stopped after reaching 3,500με
2691-3130		0.502	0.182	1.5	4.35	Stopped after reaching 3,500με
				Average:	**4.52**	
				Standard Deviation:	0.13	
				COV:	2.9%	

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Resin Digestion
Set 3

Report Number: 2691-R01 Appendix G
Purchase Order: 1081
Specification: ASTM D3171-99/D2734-94
Hotplate: H_2SO_4/H_2O_2
GEC Test Plan: GEC-TS024 Rev B

Fiber Density (g/cc): 2.50
Resin Density (g/cc): 1.140
Test Technician: Stacy Oliphant
Test Date (2691-3141 thru 3143): 12/13/2006
Test Date (2691-3144): 12/15/2006
Temperature (°C): 21.0

Fiber Volume & Void Content

Specimen ID	Global Energy Panel ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)	Fiber Volume (%)	Resin Volume (%)	Void Volume* (%)
2691-3141	SN5-0290	0.9980	1.931	0.726	0.350	1.926	52	55	-7.2
2691-3142		0.9980	1.932	0.720	0.347	1.927	50	59	-9.1
2691-3143		0.9980	1.950	0.754	0.367	1.945	55	49	-4.5
2691-3144		0.9980	1.943	0.738	0.358	1.938	55	48	-3.9
			Average:	**0.734**	**0.356**	**1.934**	**53**	**53**	**-6.2**
			Standard Deviation:	0.015	0.009	0.009	3	5	2.4
			COV:	2.0%	2.5%	0.5%	5.0%	9.6%	

*Note: A value for "Void Volume" which is less than zero may be considered equal to zero due to the precision of reporting the densities of the fibers and resin.

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Tg by TMA
Set 3

Report Number: 2691-R01 Appendix F
GEC Test Plan: GEC-TS024 Rev B
Purchase Order: 1081

Test Technician: Jeanette Francis
Test Date: 12/15/2006

Glass Transition Temperature (TMA by Flexure)

intec ID	Global Energy Panel ID	Specimen Height *(mm)*	Specimen Width *(mm)*	Specimen Depth *(mm)*	Support Span *(mm)*	Static Force *(mN)*	Ramp Rate *(°C/min)*	Tg *(°C)*	Tg *(°F)*
2691-3152	SN5-0290	0.52	20.39	4.39	15	1400	5	70	158

Glass transition temperature is determined from the deflection-temperature curve by the method of intersecting tangents.

Density

Report Number: 2340-R04
Purchase Order: Sandia5-4
Specification: ASTM D792-00

Test Technician: Denise Galasso
Test Date: 9/15/2004
Temperature (°C): 19.7

Specimen ID	Global Energy Panel ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)
2340-1	SN5-0241	0.9983	1.162	4.937	0.684	1.159
2340-2		0.9983	1.162	4.839	0.670	1.159
			Average:	**4.888**	**0.677**	**1.159**
			Standard Deviation:	0.069	0.010	0.000
			COV:	1.4%	1.4%	0.0%
2340-3	SN5-0231	0.9983	1.154	3.543	0.470	1.151
2340-4		0.9983	1.155	3.117	0.416	1.152
			Average:	**3.330**	**0.443**	**1.152**
			Standard Deviation:	0.301	0.038	0.001
			COV:	9.0%	8.6%	0.1%

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Notes: SN5-0231 is Huntsman Araldite LY 1564 Epoxy.
SN5-0241 is Jeffco 1401 Epoxy.

NEAT RESIN DENSITY

Report Number: 2490-R01
Test Specification: ASTM D792-00
Purchase Order: Sandia 5-15

Test Technician: Denise Galasso
Test Date: **5/5/2005**
Temperature (°C): **20.0**

Specimen ID	Water Density (g/cc)	Specific Gravity	Dry Weight (g)	Wet Weight (g)	Specimen Density (g/cc)
2490-3000	0.9982	1.171	12.5528	1.8255	1.168
2490-3001	0.9982	1.172	12.0722	1.7623	1.169
		Average:	**12.3125**	**1.7939**	**1.168**
		Standard Deviation:	0.3398	0.0447	0.001
		COV:	2.8%	2.5%	0.0%

Integrated Technologies Inc. certifies the above testing was completed in accordance with the listed specification.

Note: Resin is Vipel VE F010 Vinyl Ester.

Appendix E

Tabular Data for Fatigue Tests (MSU)

ELT-5500 / Epoxy GEC Panel ID 020X

(1/m)	-Log(A)	m	A
0.096377	-0.068823	10.3759	1.1717

* Intec-measured values for modulus used in "updated" calculations.

Updated Modulus / Strain Calculation

Epoxy / R=0.1 Curve Fits

σ_o (psi)=	121385	A =	1.1717
ε_o =	2.69	m =	10.38

Coupon Number	Stress (psi) max	Stress (psi) min	R	Freq. (Hz)	Strain (%)	cycles	Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$	Calculated σ-N Curve N	Calculated σ-N Curve σ (%)	Calculated ε-N Curve N	Calculated ε-N Curve ε (%)
SN5-0291-190	118858 *	*		0.5	3.28	1	4.51	2.635	0.00	0.979	0.00914	1	142228	1	3.154
SN5-0291-191	118846 *	*		0.5	3.4	1	4.51	2.635	0.00	0.979	0.00918	10	113922	10	2.526
SN5-0291-192	126450 *	*		0.5	3.4	1	4.51	2.804	0.00	1.042	-0.01776	100	91250	100	2.023
SN5-0291-124	100000	10000	0.1	1	2.82	70	4.51	2.217	1.85	0.824	0.08416	1000	73089	1000	1.621
SN5-0291-125	100000	10000	0.1	1	2.82	91	4.51	2.217	1.96	0.824	0.08416	10000	58543	10000	1.298
SN5-0291-122	90000	9000	0.1	1	2.49	163	4.51	1.996	2.21	0.741	0.12992	100000	46892	100000	1.040
SN5-0291-123	90000	9000	0.1	1	2.49	244	4.51	1.996	2.39	0.741	0.12992	1000000	37560	1000000	0.833
SN5-0291-121	80000	8000	0.1	1	2.18	729	4.51	1.774	2.86	0.659	0.18107	10000000	30085	10000000	0.667
SN5-0291-120	80000	8000	0.1	1	2.18	1291	4.51	1.774	3.11	0.659	0.18107				
SN5-0291-119	80000	8000	0.1	1	2.18	854	4.51	1.774	2.93	0.659	0.18107				
SN5-0291-116	70000	7000	0.1	2	1.88	4815	4.51	1.552	3.68	0.577	0.23907				
SN5-0291-118	70000	7000	0.1	2	1.88	2230	4.51	1.552	3.35	0.577	0.23907				
SN5-0291-117	70000	7000	0.1	2	1.88	2999	4.51	1.552	3.48	0.577	0.23907				
SN5-0291-112	60000	6000	0.1	2	1.59	6445	4.51	1.330	3.81	0.494	0.30601				
SN5-0291-110	60000	6000	0.1	2	1.59	13151	4.51	1.330	4.12	0.494	0.30601				
SN5-0291-109	60000	6000	0.1	2	1.59	11105	4.51	1.330	4.05	0.494	0.30601				
SN5-0291-104	50000	5000	0.1	2	1.31	67165	4.51	1.109	4.83	0.412	0.38519				
SN5-0291-105	50000	5000	0.1	2	1.34	41511	4.51	1.109	4.62	0.412	0.38519				
SN5-0291-106	50000	5000	0.1	2	1.31	23455	4.51	1.109	4.37	0.412	0.38519				
SN5-0291-103	40000	4000	0.1	3	1.02	389501	4.51	0.887	5.59	0.330	0.48210				
SN5-0291-107	40000	4000	0.1	3	1.09	248599	4.51	0.887	5.40	0.330	0.48210				
SN5-0291-108	40000	4000	0.1	3	1.02	614113	4.51	0.887	5.79	0.330	0.48210				
SN5-0291-102	30000	3000	0.1	4	0.75	1821361	4.51	0.665	6.26	0.247	0.60704				
SN5-0291-101	30000	3000	0.1	4	0.75	3117135	4.51	0.665	6.49	0.247	0.60704				
SN5-0291-193	110000	11000	0.1	1	3.15	40	4.51	2.439	1.60	0.906	0.04277				
SN5-0290-195	90000	9000	0.1	1	2.49	201	4.51	1.996	2.30	0.741	0.12992				
SN5-0290-196	100000	10000	0.1	1	2.82	27	4.51	2.217	1.43	0.824	0.08416				
SN5-0290-197	110000	11000	0.1	1	3.15	19	4.51	2.439	1.28	0.906	0.04277				

ELT-5500 / Vinyl Ester GEC Panel ID 029X

(1/m)	-Log(A)	m	A
0.120239	-0.080072	8.316735	1.2025

* Intec-measured values for modulus used in "updated" calculations.

Updated Modulus / Strain Calculation

VE / R=0.1 Curve Fits

σ_o (psi)=	117402	A =	1.2025
ε_o =	2.62	m =	8.32

Coupon Number	Stress (psi) max	Stress (psi) min	R	Freq. (Hz)	Strain (%)	cycles	Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-\text{Log}(\sigma/\sigma_o)$	Calculated σ-N Curve N	Calculated σ-N Curve σ (%)	Calculated ε-N Curve N	Calculated ε-N Curve ε (%)
SN5-0201-202	124026 *	*		0.5	2.7	1	4.48	2.768	0.00	1.056	-0.02384	1	141172	1	3.151
SN5-0201-201	110615 *	*		0.5	2.4	1	4.48	2.469	0.00	0.942	0.02586	10	107031	10	2.389
SN5-0201-203	117566 *	*		0.5	2.4	1	4.48	2.624	0.00	1.001	-0.00061	100	81146	100	1.811
SN5-0201-185	50000	5000	0.1	2	1.44	7286	4.48	1.116	3.86	0.426	0.37071	1000	61522	1000	1.373
SN5-0201-184	50000	5000	0.1	2	1.44	6982	4.48	1.116	3.84	0.426	0.37071	10000	46643	10000	1.041
SN5-0201-220	30000	3000	0.1	2	0.88	184487	4.48	0.670	5.27	0.256	0.59256	100000	35363	100000	0.789
SN5-0201-211	40000	4000	0.1	2	1.17	20620	4.48	0.893	4.31	0.341	0.46762	1000000	26811	1000000	0.598
SN5-0201-219	40000	4000	0.1	2	1.17	17615	4.48	0.893	4.25	0.341	0.46762	10000000	20327	10000000	0.454
SN5-0201-218	40000	4000	0.1	2	1.17	19091	4.48	0.893	4.28	0.341	0.46762				
SN5-0201-208	30000	3000	0.1	3	0.88	162416	4.48	0.670	5.21	0.256	0.59256				
SN5-0201-217	30000	3000	0.1	3	0.88	211015	4.48	0.670	5.32	0.256	0.59256				
SN5-0201-200	60000	6000	0.1	2	1.71	2491	4.48	1.339	3.40	0.511	0.29153				
SN5-0201-209	60000	6000	0.1	2	1.71	1559	4.48	1.339	3.19	0.511	0.29153				
SN5-0201-215	25000	2500	0.1	4	0.73	1431704	4.48	0.558	6.16	0.213	0.67174				
SN5-0201-205	25000	2500	0.1	4	0.73	1134970	4.48	0.558	6.05	0.213	0.67174				
SN5-0201-206	50000	5000	0.1	2	1.44	9166	4.48	1.116	3.96	0.426	0.37071				
SN5-0201-207	60000	6000	0.1	2	1.71	1549	4.48	1.339	3.19	0.511	0.29153				
SN5-0201-216	70000	7000	0.1	1	1.94	596	4.48	1.563	2.78	0.596	0.22458				
SN5-0201-213	70000	7000	0.1	1	1.94	951	4.48	1.563	2.98	0.596	0.22458				
SN5-0201-212	70000	7000	0.1	1	1.94	494	4.48	1.563	2.69	0.596	0.22458				
SN5-0201-214	80000	8000	0.1	1	2.15	227	4.48	1.786	2.36	0.681	0.16659				
SN5-0201-204	80000	8000	0.1	1	2.15	251	4.48	1.786	2.40	0.681	0.16659				
SN5-0201-230	80000	8000	0.1	1	2.15	133	4.48	1.786	2.12	0.681	0.16659				
SN5-0201-245	90000	9000	0.1	1	2.33	92	4.48	2.009	1.96	0.767	0.11543				
SN5-0201-240	90000	9000	0.1	1	2.33	112	4.48	2.009	2.05	0.767	0.11543				
SN5-0201-241	90000	9000	0.1	1	2.33	87	4.48	2.009	1.94	0.767	0.11543				
SN5-0201-242	100000	10000	0.1	1	2.61	35	4.48	2.232	1.54	0.852	0.06968				
SN5-0201-244	100000	10000	0.1	1	2.61	14	4.48	2.232	1.15	0.852	0.06968				
SN5-0201-243	100000	10000	0.1	1	2.61	38	4.48	2.232	1.58	0.852	0.06968				

ELT-5500 / Epoxy GEC Panel ID 020X

(1/m)	-Log(A)	m	A
0.061938	-0.011977	16.14512	1.0280

* Intec-measured values for modulus used in "updated" calculations.

Updated Modulus / Strain Calculation

Epoxy / R=10 Curve Fits

σ_o (psi)=	80078	A =	1.0280
ε_o =	1.77	m =	16.15

Coupon Number	Stress (psi) max	min	R	Freq. (Hz)	Strain (%)	cycles	Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-\text{Log}(\sigma/\sigma_o)$	Calculated σ-N Curve N	σ (%)	Calculated ε-N Curve N	ε (%)
SN5-0291-230	-74616 *	*		0.5	-1.750727	1	4.52	1.651	0.00	0.932	0.03068	1	82317	1	1.821
SN5-0291-214	-70709 *	*		0.5	-1.659057	1	4.52	1.564	0.00	0.883	0.05404	10	71376	10	1.579
SN5-0291-224	-69336 *	*		0.5	-1.626842	1	4.52	1.534	0.00	0.866	0.06255	100	61889	100	1.369
SN5-0291-229	-72667 *	*		0.5	-1.704998	1	4.52	1.608	0.00	0.907	0.04218	1000	53663	1000	1.187
SN5-0291-203	-89768 *	*		0.5	-2.106241	1	4.52	1.986	0.00	1.121	-0.04961	10000	46531	10000	1.029
SN5-0291-223	-89320 *	*		0.5	-2.09573	1	4.52	1.976	0.00	1.115	-0.04744	100000	40346	100000	0.893
SN5-0291-206	-95992 *	*		0.5	-2.252276	1	4.52	2.124	0.00	1.199	-0.07872	1000000	34983	1000000	0.774
SN5-0291-201	-78216 *	*		0.5	-1.835195	1	4.52	1.730	0.00	0.977	0.01022	10000000	30334	10000000	0.671
SN5-0291-202	-50000	-5000	10	3	-1.173158	4122	4.52	1.106	3.62	0.624	0.20454				
SN5-0291-207	-30000	-3000	10	5	-0.703895	1500000	4.52	0.664	6.18	0.375	0.42639				
SN5-0291-200	-30000	-3000	10	5	-0.703895	2500000	4.52	0.664	6.40	0.375	0.42639				
SN5-0291-208	-70000	-7000	10	1	-1.642421	17	4.52	1.549	1.23	0.874	0.05842				
SN5-0291-240	-70000	-7000	10	1	-1.642421	83	4.52	1.549	1.92	0.874	0.05842				
SN5-0291-204	-70000	-7000	10	1	-1.642421	36	4.52	1.549	1.56	0.874	0.05842				
SN5-0291-237	-70000	-7000	10	1	-1.642421	63	4.52	1.549	1.80	0.874	0.05842				
SN5-0291-242	-70000	-7000	10	1	-1.642421	14	4.52	1.549	1.15	0.874	0.05842				
SN5-0291-217	-50000	-5000	10	2	-1.173158	18834	4.52	1.106	4.27	0.624	0.20454				
SN5-0291-215	-50000	-5000	10	2	-1.173158	13878	4.52	1.106	4.14	0.624	0.20454				

ELT-5500 / Vinyl Ester GEC Panel ID 029X

(1/m)	-Log(A)	m	A
0.048396	-0.017422	20.66304	1.0409

* Intec-measured values for modulus used in "updated" calculations.

Updated Modulus / Strain Calculation

VE / R=10 Curve Fits

σ_o (psi)=	94892	A =	1.0409
ε_o =	1.88	m =	20.66

Coupon Number	Stress (psi) max	min	R	Freq. (Hz)	Strain (%)	cycles	Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$	Calculated σ-N Curve N	σ (%)	Calculated ε-N Curve N	ε (%)
SN5-0201-161	-89254 *	*		0.5	-1.916967	1	5.05	1.767	0.00	0.941	0.02660	1	98776	1	1.956
SN5-0201-173	-99282 *	*		0.5	-2.132345	1	5.05	1.966	0.00	1.046	-0.01964	10	88360	10	1.750
SN5-0201-174	-96140 *	*		0.5	-2.064863	1	5.05	1.904	0.00	1.013	-0.00567	100	79042	100	1.565
SN5-0201-151	-104001 *	*		0.5	-2.233698	1	5.05	2.059	0.00	1.096	-0.03981	1000	70707	1000	1.400
SN5-0201-157	-80000	-8000	10	1	-1.718213	242	5.05	1.584	2.38	0.843	0.07414	10000	63251	10000	1.252
SN5-0201-163	-80000	-8000	10	1	-1.718213	81	5.05	1.584	1.91	0.843	0.07414	100000	56581	100000	1.120
SN5-0201-160	-80000	-8000	10	1	-1.718213	1095	5.05	1.584	3.04	0.843	0.07414	1000000	50615	1000000	1.002
SN5-0201-166	-70000	-7000	10		-1.503436	3110	5.05	1.386	3.49	0.738	0.13213	10000000	45277	10000000	0.897
SN5-0201-133	-70000	-7000	10		-1.503436	1265	5.05	1.386	3.10	0.738	0.13213				
SN5-0201-162	-70000	-7000	10		-1.503436	712	5.05	1.386	2.85	0.738	0.13213				
SN5-0201-140	-60000	-6000	10		-1.28866	30875	5.05	1.188	4.49	0.632	0.19908				
SN5-0201-152	-60000	-6000	10		-1.28866	57183	5.05	1.188	4.76	0.632	0.19908				
SN5-0201-170	-50000	-5000	10		-1.073883	41810	5.05	0.990	4.62	0.527	0.27826				

ELT-5500 / Epoxy GEC Panel ID 020X

(1/m)	-Log(A)	m	A
0.103982	-0.082788	9.617064	1.2100

ε-N Curve Based on MSU-measured Strains

Epoxy / R=0.1 Curve Fits

σ_o (psi)=	121385	A =	1.2100
ε_o =	3.36	m =	9.62

Coupon Number	Stress (psi) max	min	R	Freq. (Hz)	Strain (%)	cycles	Log(N)	$\varepsilon/\varepsilon_o$	$-Log(\varepsilon/\varepsilon_o)$	Calculated ε-N Curve N	ε (%)
SN5-0291-190	118858 *	*		0.5	3.28	1	0.00	0.976	0.01047	1	4.066
SN5-0291-191	118846 *	*		0.5	3.4	1	0.00	1.012	-0.00514	10	3.200
SN5-0291-192	126450 *	*		0.5	3.4	1	0.00	1.012	-0.00514	100	2.519
SN5-0291-124	100000	10000	0.1	1	2.82	70	1.85	0.839	0.07609	1000	1.982
SN5-0291-125	100000	10000	0.1	1	2.82	91	1.96	0.839	0.07609	10000	1.560
SN5-0291-122	90000	9000	0.1	1	2.49	163	2.21	0.741	0.13014	100000	1.228
SN5-0291-123	90000	9000	0.1	1	2.49	244	2.39	0.741	0.13014	1000000	0.967
SN5-0291-121	80000	8000	0.1	1	2.18	729	2.86	0.649	0.18788	10000000	0.761
SN5-0291-120	80000	8000	0.1	1	2.18	1291	3.11	0.649	0.18788		
SN5-0291-119	80000	8000	0.1	1	2.18	854	2.93	0.649	0.18788		
SN5-0291-116	70000	7000	0.1	2	1.88	4815	3.68	0.560	0.25218		
SN5-0291-118	70000	7000	0.1	2	1.88	2230	3.35	0.560	0.25218		
SN5-0291-117	70000	7000	0.1	2	1.88	2999	3.48	0.560	0.25218		
SN5-0291-112	60000	6000	0.1	2	1.59	6445	3.81	0.473	0.32494		
SN5-0291-110	60000	6000	0.1	2	1.59	13151	4.12	0.473	0.32494		
SN5-0291-109	60000	6000	0.1	2	1.59	11105	4.05	0.473	0.32494		
SN5-0291-104	50000	5000	0.1	2	1.31	67165	4.83	0.390	0.40907		
SN5-0291-105	50000	5000	0.1	2	1.34	41511	4.62	0.399	0.39923		
SN5-0291-106	50000	5000	0.1	2	1.31	23455	4.37	0.390	0.40907		
SN5-0291-103	40000	4000	0.1	3	1.02	389501	5.59	0.304	0.51774		
SN5-0291-107	40000	4000	0.1	3	1.09	248599	5.40	0.324	0.48891		
SN5-0291-108	40000	4000	0.1	3	1.02	614113	5.79	0.304	0.51774		
SN5-0291-102	30000	3000	0.1	4	0.75	1821361	6.26	0.223	0.65128		
SN5-0291-101	30000	3000	0.1	4	0.75	3117135	6.49	0.223	0.65128		
SN5-0291-193	110000	11000	0.1	1	3.15	40	1.60	0.938	0.02803		
SN5-0290-195	90000	9000	0.1	1	2.49	201	2.30	0.741	0.13014		
SN5-0290-196	100000	10000	0.1	1	2.82	27	1.43	0.839	0.07609		
SN5-0290-197	110000	11000	0.1	1	3.15	19	1.28	0.938	0.02803		

ELT-5500 / Vinyl Ester GEC Panel ID 029X

(1/m)	-Log(A)	m	A
0.098984	-0.120646	10.1026	1.3202

ε-N Curve Based on MSU-measured Strains

VE / R=0.1 Curve Fits

σ_o (psi)=	117402	A =	1.3202
ε_o =	2.50	m =	10.10

Coupon Number	Stress (psi) max	min	R	Freq. (Hz)	Strain (%)	cycles	Log(N)	$\varepsilon/\varepsilon_o$	$-Log(\varepsilon/\varepsilon_o)$	Calculated ε-N Curve N	ε (%)
SN5-0201-202	124026 *	*		0.5	2.7	1	0.00	1.080	-0.03342	1	3.301
SN5-0201-201	110615 *	*		0.5	2.4	1	0.00	0.960	0.01773	10	2.628
SN5-0201-203	117566 *	*		0.5	2.4	1	0.00	0.960	0.01773	100	2.092
SN5-0201-185	50000	5000	0.1	2	1.44	7286	3.86	0.576	0.23958	1000	1.666
SN5-0201-184	50000	5000	0.1	2	1.44	6982	3.84	0.576	0.23958	10000	1.326
SN5-0201-220	30000	3000	0.1	2	0.88	184487	5.27	0.352	0.45346	100000	1.056
SN5-0201-211	40000	4000	0.1	2	1.17	20620	4.31	0.468	0.32975	1000000	0.841
SN5-0201-219	40000	4000	0.1	2	1.17	17615	4.25	0.468	0.32975	10000000	0.669
SN5-0201-218	40000	4000	0.1	2	1.17	19091	4.28	0.468	0.32975		
SN5-0201-208	30000	3000	0.1	3	0.88	162416	5.21	0.352	0.45346		
SN5-0201-217	30000	3000	0.1	3	0.88	211015	5.32	0.352	0.45346		
SN5-0201-200	60000	6000	0.1	2	1.71	2491	3.40	0.684	0.16494		
SN5-0201-209	60000	6000	0.1	2	1.71	1559	3.19	0.684	0.16494		
SN5-0201-215	25000	2500	0.1	4	0.73	1431704	6.16	0.292	0.53462		
SN5-0201-205	25000	2500	0.1	4	0.73	1134970	6.05	0.292	0.53462		
SN5-0201-206	50000	5000	0.1	2	1.44	9166	3.96	0.576	0.23958		
SN5-0201-207	60000	6000	0.1	2	1.71	1549	3.19	0.684	0.16494		
SN5-0201-216	70000	7000	0.1	1	1.94	596	2.78	0.776	0.11014		
SN5-0201-213	70000	7000	0.1	1	1.94	951	2.98	0.776	0.11014		
SN5-0201-212	70000	7000	0.1	1	1.94	494	2.69	0.776	0.11014		
SN5-0201-214	80000	8000	0.1	1	2.15	227	2.36	0.860	0.06550		
SN5-0201-204	80000	8000	0.1	1	2.15	251	2.40	0.860	0.06550		
SN5-0201-230	80000	8000	0.1	1	2.15	133	2.12	0.860	0.06550		
SN5-0201-245	90000	9000	0.1	1	2.33	92	1.96	0.932	0.03058		
SN5-0201-240	90000	9000	0.1	1	2.33	112	2.05	0.932	0.03058		
SN5-0201-241	90000	9000	0.1	1	2.33	87	1.94	0.932	0.03058		
SN5-0201-242	100000	10000	0.1	1	2.61	35	1.54	1.044	-0.01870		
SN5-0201-244	100000	10000	0.1	1	2.61	14	1.15	1.044	-0.01870		
SN5-0201-243	100000	10000	0.1	1	2.61	38	1.58	1.044	-0.01870		

GEC I.D. SN5-212X (same layup as SN5-021X, but without fiberglass facings)
Toray pregreg carbon

(1/m)	-Log(A)	m	A
0.031802	-0.008442	31.44496	1.0196

* MSU-measured values for modulus used in "updated" calculations.

Toray Coupon	R-Value	Maximum Stress PSI	Minimum stress PSI	Frequency Hz	0.1 - 0.3% Modulus (msi)	Maximum Strain %	cycles to failure	thickness (mm)	VF
2429-0304	static	313361		0.5"/sec	17.93	1.61	1	2.362	0.588
2429-0308	static	276653		0.5"/sec	17.88	1.45	1	2.426	0.573
2429-0305	static	282349		0.5"/sec	17.78	1.51	1	2.413	0.576
2429-0301	static	277662		1	19.68	1.42	1	1.956	0.710
2429-0302	0.1	260000		1	21.22	1.14	123	2.064	0.673
2429-0303	0.1	270000		1	19.73	1.14	194	2.159	0.643
2429-0306	0.1	275000		1	17.83	1.36	32	2.426	0.573
2429-0311	0.1	230000		1	20.04	1.09	1272	2.324	0.598
2429-0315	0.1	230000		2	19.74	1.1	81743	2.299	0.604
2429-0316	0.1	230000		2	19.18	1.1	6248	2.362	0.588
2429-0307	0.1	215000		2	17.71	1.16	4204	2.413	0.576
2429-0312	0.1	200000		2	20.02	0.96	17873	2.413	0.576
2429-0314	0.1	200000		2	19.50	0.98	128092	2.400	0.579
2429-0313	0.1	190000		2	18.00	1.02	345949	2.388	0.582
2429-0310	0.1	190000		2	17.72	1.03	102971	2.413	0.576
				Average =	18.93				

Updated Modulus / Strain Calculation

Epoxy / R=0.1 Curve Fits

σ_o =	287506	A =	1.0196
ε_o =	1.52	m =	31.44

Coupon	Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-\text{Log}(\sigma/\sigma_o)$	Calculated s-N Curve N	Calculated s-N Curve σ (%)	Calculated e-N Curve N	Calculated e-N Curve ε (%)
2429-0304	18.9	1.655	0.00	1.090	-0.03740	1	293150	1	1.549
2429-0308	18.9	1.461	0.00	0.962	0.01671	10	272451	10	1.439
2429-0305	18.9	1.491	0.00	0.982	0.00786	100	253213	100	1.338
2429-0301	18.9	1.467	0.00	0.966	0.01513	1000	235334	1000	1.243
2429-0302	18.9	1.373	2.09	0.904	0.04367	10000	218717	10000	1.155
2429-0303	18.9	1.426	2.29	0.939	0.02728	100000	203274	100000	1.074
2429-0306	18.9	1.453	1.51	0.957	0.01931	1000000	188921	1000000	0.998
2429-0311	18.9	1.215	3.10	0.800	0.09692	10000000	175581	10000000	0.927
2429-0315	18.9	1.215	4.91	0.800	0.09692				
2429-0316	18.9	1.215	3.80	0.800	0.09692				
2429-0307	18.9	1.136	3.62	0.748	0.12621				
2429-0312	18.9	1.056	4.25	0.696	0.15762				
2429-0314	18.9	1.056	5.11	0.696	0.15762				
2429-0313	18.9	1.004	5.54	0.661	0.17989				
2429-0310	18.9	1.004	5.01	0.661	0.17989				

GEC I.D. SN5-213X (same layup as SN5-024X, but without fiberglass facings)
Zoltek pregreg carbon

(1/m)	-Log(A)	m	A
0.026546	0.009169	37.6698	0.9791

* MSU-measured values for modulus used in "updated" calculations.

ZOLTEK Coupon	R-Value	Maximum Stress PSI	Minimum stress PSI	Frequency Hz	0.1 - 0.3% Modulus (msi)	Maximum Strain %	cycles to failure	thickness (mm)	VF
2429-0409	static	269350		0.5"/sec	18.6868	1.34	1	2.667	0.521
2429-0410	static	256637		0.5"/sec	19.9384	1.25	1	2.616	0.531
2429-0408	static	263117		0.5"/sec	18.6775	1.34	1	2.705	0.513
2429-0402	0.1	200000		1	19.59	0.984	1049	2.489	0.558
2429-0407	0.1	200000		1	17.64	1.02	2906	2.718	0.511
2429-0403	0.1	200000		1	18.83	1.03	3141	2.591	0.536
2429-0411	0.1	190000		2	18.3376	0.99	300021	2.515	0.552
2429-0412	0.1	190000		2	18.48685	0.96	497630	2.306	0.602
2429-0401	0.1	180000		2	19.1558	0.88	1096651	2.267	0.613
				Avg =	18.81588				

Updated Modulus / Strain Calculation

Epoxy / R=0.1 Curve Fits

σ_o =	263035	A =	0.9791
ε_o =	1.40	m =	37.67

Coupon	Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-\text{Log}(\sigma/\sigma_o)$	Calculated σ-N Curve N	Calculated σ-N Curve σ (%)	Calculated ε-N Curve N	Calculated ε-N Curve ε (%)
2429-0409	18.82	1.432	0.00	1.024	-0.01030	1	257539	1	1.369
2429-0410	18.82	1.364	0.00	0.976	0.01069	10	242269	10	1.288
2429-0408	18.82	1.398	0.00	1.000	-0.00014	100	227903	100	1.211
2429-0402	18.82	1.063	3.02	0.760	0.11898	1000	214390	1000	1.139
2429-0407	18.82	1.063	3.46	0.760	0.11898	10000	201678	10000	1.072
2429-0403	18.82	1.063	3.50	0.760	0.11898	100000	189719	100000	1.008
2429-0411	18.82	1.010	5.48	0.722	0.14126	1000000	178470	1000000	0.949
2429-0412	18.82	1.010	5.70	0.722	0.14126	10000000	167888	10000000	0.892
2429-0401	18.82	0.957	6.04	0.684	0.16474				

MATERIAL "P2B" from DOE/MSU Database
Lay-up = (±45/08C/ 45), Newport carbon NB307-D1 prepreg 0 , 300/m2 with glass 0/90 prepreg for ±45 , 298 g/m2

(1/m)	-Log(A)	m	A
0.020873	-0.01289	47.90772	1.0301

* Intec-measured values for modulus used in "updated" calculations.

Epoxy / R=0.1 Curve Fits

σ_o =	1496.4	A =	1.0301
ε_o =	1.45	m =	47.91

coupon	Max Stress MPa	R-value	Frequency Hz	Modulus GPa	Strain %	Cycles	comments R=runout	Updated Modulus / Strain Calculation: Modulus* Gpa	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-\text{Log}(\sigma/\sigma_o)$
P2B-402	1597 *		13	98.2	1.49	1		103.5	1.543	0.00	1.067	-0.02831
P2B-400	1405 *		13	96.4	1.31	1		103.5	1.357	0.00	0.939	0.02743
P2B-401	1487 *		13	95.4	1.39	1		103.5	1.437	0.00	0.994	0.00268
P2B-178	1605 *		13	107	1.35	1		103.5	1.550	0.00	1.072	-0.03035
P2B-1100	1664 *		1	107	1.42	1		103.5	1.607	0.00	1.112	-0.04600
P2B-1102	1544 *		1	----	1.45	1		103.5	1.492	0.00	1.032	-0.01372
P2B-900	1597 *		6.35	----	1.49	1		103.5	1.543	0.00	1.067	-0.02833
P2B-901	1473 *		6.35	----	1.38	1		103.5	1.423	0.00	0.984	0.00686
P2B-902	1582 *		6.35	----	1.48	1		103.5	1.529	0.00	1.057	-0.02425
P2B-903	1605 *		6.35	----	1.50	1		103.5	1.551	0.00	1.073	-0.03050
P2B-904	1594 *		6.35	----	1.49	1		103.5	1.540	0.00	1.065	-0.02734
P2B-905	1500 *		13	----	1.40	1		103.5	1.450	0.00	1.003	-0.00116
P2B-906	1520 *		13	----	1.42	1		103.5	1.468	0.00	1.016	-0.00668
P2B-907	1665 *		13	----	1.56	1		103.5	1.609	0.00	1.113	-0.04633
P2B-908	1495 *		13	----	1.40	1		103.5	1.445	0.00	0.999	0.00029
P2B-909	1549 *		13	----	1.45	1		103.5	1.497	0.00	1.035	-0.01509
P2B-910	1511 *		0.01	----	1.41	1		103.5	1.460	0.00	1.010	-0.00423
P2B-911	1501 *		0.01	----	1.40	1		103.5	1.450	0.00	1.003	-0.00132
P2B-912	1559 *		0.01	----	1.46	1		103.5	1.506	0.00	1.042	-0.01779
P2B-913	1497 *		0.01	----	1.40	1		103.5	1.447	0.00	1.001	-0.00030
P2B-914	1514 *		0.01	----	1.42	1		103.5	1.463	0.00	1.012	-0.00511
P2B-307	1103	0.1	1	----	1.10	449693		103.5	1.066	5.65	0.737	0.13239
P2B-303	1034	0.1	1	----	1.03	5000000		103.5	0.999	6.70	0.691	0.16042
P2B-293	1172	0.1	1	----	1.10	4172383		103.5	1.133	6.62	0.783	0.10606
P2B-170	1241	0.1	1	----	1.16	665487		103.5	1.199	5.82	0.829	0.08124
P2B-176	1379	0.1	1	----	1.29	780		103.5	1.332	2.89	0.922	0.03548
P2B-180	1379	0.1	1	----	1.29	1030		103.5	1.332	3.01	0.922	0.03548
P2B-173	1379	0.1	1	----	1.29	372		103.5	1.332	2.57	0.922	0.03548
P2B-182	1310	0.1	1	----	1.23	1782		103.5	1.266	3.25	0.875	0.05776
P2B-174	1310	0.1	1	----	1.23	2711		103.5	1.266	3.43	0.875	0.05776
P2B-181	1310	0.1	1	----	1.23	619		103.5	1.266	2.79	0.875	0.05776
P2B-638	1310	0.1	1	----	1.23	926		103.5	1.266	2.97	0.875	0.05776
P2B-639	1241	0.1	1	----	1.16	31542		103.5	1.199	4.50	0.829	0.08124
P2B-172	1448	0.1	1	100	1.35	4		103.5	1.399	0.60	0.968	0.01429
P2B-175	1448	0.1	1	97.3	1.36	2		103.5	1.399	0.30	0.968	0.01429
P2B-179	1413	0.1	1	99.2	1.32	797		103.5	1.366	2.90	0.945	0.02476
P2B-611	1413	0.1	1	----	1.32	32		103.5	1.366	1.51	0.945	0.02476
P2B-624	1413	0.1	1	----	1.32	99		103.5	1.366	2.00	0.945	0.02476
P2B-618	1276	0.1	1	----	1.19	18903		103.5	1.232	4.28	0.852	0.06934
P2B-640	1241	0.1	1	----	1.16	7140		103.5	1.199	3.85	0.829	0.08124
P2B-644	1241	0.1	1	----	1.16	77938		103.5	1.199	4.89	0.829	0.08124

Calculated σ-N Curve: N	σ (%)	Calculated ε-N Curve: N	ε (%)
1	1541.5	1	1.489
10	1469.1	10	1.419
100	1400.2	100	1.353
1000	1334.5	1000	1.289
10000	1271.9	10000	1.229
100000	1212.2	100000	1.171
1000000	1155.3	1000000	1.116
10000000	1101.1	10000000	1.064

GEC I.D. SN5-211X
Toray pregreg carbon

* Intec-measured values for modulus used in "updated" calculations.
** Modulus used in MSU calculations incorrect for panel with glass facings.

(1/m)	-Log(A)	m	A
0.02152	0.00415	46.46944	0.9905

Updated Modulus / Strain Calculation

Epoxy / R=0.1 Curve Fits

σ_o =	178471	A =	0.9905
ε_o =	1.12	m =	46.47

Toray Coupon	R-Value	Maximum Stress PSI	Minimum stress PSI	Frequency Hz	0.1 - 0.3% Modulus** (msi)	Maximum Strain %	cycles to failure	thickness (mm)	VF		Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$	Calculated σ-N Curve N	Calculated σ-N Curve σ (%)	Calculated ε-N Curve N	Calculated ε-N Curve ε (%)
2429-0104	static		-169342	0.5"/sec	17.86	-0.947988	1	3.048	0.559		16.0	1.058	0.000	0.949	0.02280	1	176773	1	1.105
2429-0115	static		-193656	0.5"/sec	17.86	-1.0841	1	2.883	0.591		16.0	1.210	0.000	1.085	-0.03546	10	168227	10	1.051
2429-0109	static		-172414	0.5"/sec	17.86	-0.965186	1	3.289	0.518		16.0	1.078	0.000	0.966	0.01499	100	160095	100	1.001
2429-0103	10	-12500	-125000	3	17.86	-0.699759	1500000	2.972	0.573	RO	16.0	0.781	6.176	0.700	0.15466	1000	152355	1000	0.952
2429-0101	10	-14000	-140000	2	17.86	-0.78373	3410	3.099	0.550		16.0	0.875	3.533	0.784	0.10544	10000	144990	10000	0.906
2429-0120	10	-13000	-130000	3	17.86	-0.72	16302	3.366	0.506		16.0	0.813	4.212	0.728	0.13762	100000	137981	100000	0.862
2429-0105	10	-13000	-130000	3	17.86	-0.72	624418	2.959	0.576		16.0	0.813	5.795	0.728	0.13762	1000000	131310	1000000	0.821
2429-0108	10	-13000	-130000	3	17.86	-0.72	1136282	2.654	0.642		16.0	0.813	6.055	0.728	0.13762	10000000	124963	10000000	0.781
2429-0107	10	-13500	-135000	3	17.86	-0.75	1500000	2.807	0.607	RO	16.0	0.844	6.176	0.756	0.12123				
2429-0102	10	-14000	-140000	2	17.86	-0.78373	272401	3.200	0.532		16.0	0.875	5.435	0.784	0.10544				
2429-0114	10	-14000	-140000	2	17.86	-0.78	119078	2.997	0.569		16.0	0.875	5.076	0.784	0.10544				
2429-0113	10	-15000	-150000	1	17.86	-0.84	11296	2.972	0.573		16.0	0.938	4.053	0.840	0.07548				
2429-0112	10	-15000	-150000	1	17.86	-0.84	74401	3.056	0.558		16.0	0.938	4.872	0.840	0.07548				
2429-0111	10	-16000	-160000	1	17.86	-0.9	89	3.150	0.541		16.0	1.000	1.949	0.897	0.04745				

GEC I.D. SN5-214X
Zoltek pregreg carbon

* Intec-measured values for modulus used in "updated" calculations.
** Modulus used in MSU calculations incorrect for panel with glass facings.

(1/m)	-Log(A)	m	A
0.036272	0.008087	27.56963	0.9816

Updated Modulus / Strain Calculation

Epoxy / R=0.1 Curve Fits

σ_o =	182548	A =	0.9816
ε_o =	1.21	m =	27.57

ZOLTEK Coupon	R-Value	Maximum Stress PSI	Minimum stress PSI	Frequency Hz	0.1 - 0.3% Modulus** (msi)	Maximum Strain %	cycles to failure	thickness (mm)	VF	Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$	Calculated σ-N Curve N	Calculated σ-N Curve σ (%)	Calculated ε-N Curve N	Calculated ε-N Curve ε (%)
2429-0214	static		-190852	0.5"/sec	17.89	-1.0668	1	3.023	0.564	15.1	1.264	0.00	1.045	-0.01932	1	179180	1	1.187
2429-0203	static		-185396	0.5"/sec	17.89	-1.0363	1	3.048	0.559	15.1	1.228	0.00	1.016	-0.00672	10	164823	10	1.092
2429-0217	static		-171395	0.5"/sec	17.89	-0.9580	1	3.251	0.524	15.1	1.135	0.00	0.939	0.02738	100	151616	100	1.004
2429-0204	10	-14000	-140000	1	17.89	-0.7826	695	3.188	0.535	15.1	0.927	2.84	0.767	0.11525	1000	139468	1000	0.924
2429-0221	10	-14000	-140000	1	17.89	-0.7826	169	2.819	0.604	15.1	0.927	2.23	0.767	0.11525	10000	128293	10000	0.850
2429-0209	10	-12000	-120000	3	17.89	-0.6708	42811	3.378	0.504	15.1	0.795	4.63	0.657	0.18220	100000	118013	100000	0.782
2429-0216	10	-10000	-100000	4	17.89	-0.5590	1500000	2.769	0.615	15.1	0.662	6.18	0.548	0.26138	1000000	108557	1000000	0.719
2429-0215	10	-14000	-140000	1	17.89	-0.7826	553	2.946	0.578	15.1	0.927	2.74	0.767	0.11525	10000000	99859	10000000	0.661
2429-0206	10	-11000	-110000	4	17.89	-0.6149	1435681	3.213	0.530	15.1	0.728	6.16	0.603	0.21998				
2429-0220	10	-12000	-120000	3	17.89	-0.6708	756881	2.870	0.594	15.1	0.795	5.88	0.657	0.18220				
2429-0211	10	-13000	-130000	2	17.89	-0.73	244826	3.239	0.526									
2429-0219	10	-13000	-130000	2	17.89	-0.73	363266	3.112	0.548									

MATERIAL "P2B" from DOE/MSU Database
Lay-up = (±45/08C/ 45), Newport carbon NB307-D1 prepreg 0 , 300/m2 with glass 0/90 prepreg for ±45 , 298 g/m2

(1/m)	-Log(A)	m	A
0.02171	0.00346	46.06093	0.992054

* Intec-measured values for modulus used in "updated" calculations.

Updated Modulus / Strain Calculation

Epoxy / R=10 Curve Fits

σ_o =	1047.0	A =	0.9921
ε_o =	1.08	m =	46.06

coupon	Max Stress MPa	R-value	Frequency Hz	Modulus GPa	Strain %	Cycles	comments R=runout	Modulus* Gpa	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$
P2B-210	-1079 *		13	96.7	-1.06	1		95.91	1.116	0.00	1.031	-0.01322
P2B-211	-1062 *		13	96.7	-1.04	1		95.91	1.098	0.00	1.014	-0.00599
P2B-580	-1052 *		13	96.7	-1.03	1		95.91	1.088	0.00	1.005	-0.00220
P2B-579	-1022 *		13	96.7	-1.00	1		95.91	1.057	0.00	0.976	0.01038
P2B-584	-1070 *		13	96.7	-1.05	1		95.91	1.106	0.00	1.022	-0.00940
P2B-740	-1002 *		13	96.7	-0.98	1		95.91	1.037	0.00	0.957	0.01887
P2B-741	-1025 *		13	96.7	-1.00	1		95.91	1.060	0.00	0.979	0.00930
P2B-742	-1039 *		13	96.7	-1.02	1		95.91	1.074	0.00	0.992	0.00344
P2B-743	-1189 *		13	96.7	-1.17	1		95.91	1.229	0.00	1.136	-0.05520
P2B-744	-1113 *		13	96.7	-1.09	1		95.91	1.151	0.00	1.064	-0.02675
P2B-745	-962 *		13	96.7	-0.94	1		95.91	0.995	0.00	0.919	0.03669
P2B-746	-1069 *		13	96.7	-1.05	1		95.91	1.105	0.00	1.021	-0.00891
P2B-747	-1069 *		13	96.7	-1.05	1		95.91	1.106	0.00	1.021	-0.00914
P2B-748	-983 *		13	96.7	-0.96	1		95.91	1.017	0.00	0.939	0.02724
P2B-749	-1069 *		13	96.7	-1.05	1		95.91	1.106	0.00	1.021	-0.00911
P2B-750	-1090 *		13	96.7	-1.07	1		95.91	1.127	0.00	1.041	-0.01738
P2B-751	-958 *		13	96.7	-0.94	1		95.91	0.991	0.00	0.915	0.03852
P2B-752	-1003 *		13	96.7	-0.98	1		95.91	1.037	0.00	0.958	0.01877
P2B-753	-1036 *		13	96.7	-1.02	1		95.91	1.071	0.00	0.989	0.00465
P2B-585	-896	10	1	96.7	-0.88	141	25	95.91	0.927	2.15	0.856	0.06746
P2B-583	-896	10	1	96.7	-0.88	43	25	95.91	0.927	1.63	0.856	0.06746
P2B-212	-896	10	1	96.7	-0.88	65	25	95.91	0.927	1.81	0.856	0.06746
P2B-213	-827	10	3	96.7	-0.81	344025	25	95.91	0.856	5.54	0.790	0.10222
P2B-203	-827	10	3	96.7	-0.81	43173	25	95.91	0.856	4.64	0.790	0.10222
P2B-204	-827	10	3	96.7	-0.81	182396	25	95.91	0.856	5.26	0.790	0.10222
P2B-205	-793	10	4	96.7	-0.78	383644	25	95.91	0.820	5.58	0.757	0.12071
P2B-207	-758	10	4	96.7	-0.74	625816		95.91	0.784	5.80	0.724	0.14001
P2B-206	-758	10	4	96.7	-0.74	1926512		95.91	0.784	6.28	0.724	0.14001
P2B-313A	-758	10	4	96.7	-0.74	3122463		95.91	0.784	6.49	0.724	0.14001
P2B-582	-862	10	1	96.7	-0.84	1350		95.91	0.891	3.13	0.823	0.08450
P2B-589	-862	10	1	96.7	-0.84	2495		95.91	0.891	3.40	0.823	0.08450
P2B-586	-862	10	1	96.7	-0.84	4950		95.91	0.891	3.69	0.823	0.08450

Calculated σ-N Curve N	Calculated σ-N Curve σ (%)	Calculated ε-N Curve N	Calculated ε-N Curve ε (%)
1	1038.7	1	1.074
10	988.0	10	1.022
100	939.8	100	0.972
1000	894.0	1000	0.925
10000	850.4	10000	0.879
100000	809.0	100000	0.837
1000000	769.5	1000000	0.796
10000000	732.0	10000000	0.757

GEC I.D. SN5-211X
Toray pregreg carbon

* Intec-measured values for modulus used in "updated" calculations.
** Modulus used in MSU calculations incorrect for panel with glass facings.

(1/m)	-Log(A)	m	A
0.057734	0.002279	17.32073	0.9948

Epoy / R=0.1 Curve Fits

σ_o =	178471	A =	0.9948
ε_o =	1.12	m =	17.32

Toray Coupon	R-Value	Maximum Stress PSI	Minimum stress PSI	Frequency Hz	0.1 - 0.3% Modulus** (msi)	Maximum Strain %	cycles to failure	thickness (mm)	VF
2429-0104	static		-169342	0.5"/sec	17.86	-0.947988	1	3.048	0.559
2429-0115	static		-193656	0.5"/sec	17.86	-1.0841	1	2.883	0.591
2429-0109	static		-172414	0.5"/sec	17.86	-0.965186	1	3.289	0.518
2429-0117	-1	90000	-90000	1		0.5	174889	3.233	0.527
2429-0106	-1	90000	-90000	1		0.5	368281	2.819	0.604
2429-0110	-1	110000	-110000	1		0.62	7011	3.175	0.537
2429-0118	-1	80000	-80000	2		0.45	341552	3.226	0.528
2429-0119	-1	110000	-110000	1		0.62	1642	3.302	0.516
2429-0116	-1	80000	-80000	2		0.45	858630	2.705	0.630

Updated Modulus / Strain Calculation

Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$	Calculated s-N Curve N	σ (%)	Calculated e-N Curve N	ε (%)
16.0	1.058	0.000	0.949	0.02280	1	177537	1	1.110
16.0	1.210	0.000	1.085	-0.03546	10	155437	10	0.971
16.0	1.078	0.000	0.966	0.01499	100	136088	100	0.851
16.0	0.563	5.243	0.504	0.29732	1000	119147	1000	0.745
16.0	0.563	5.566	0.504	0.29732	10000	104316	10000	0.652
16.0	0.688	3.846	0.616	0.21017	100000	91331	100000	0.571
16.0	0.500	5.533	0.448	0.34848	1000000	79962	1000000	0.500
16.0	0.688	3.215	0.616	0.21017	10000000	70008	10000000	0.438
16.0	0.500	5.934	0.448	0.34848				

GEC I.D. SN5-214X
Zoltek pregreg carbon

* Intec-measured values for modulus used in "updated" calculations.
** Modulus used in MSU calculations incorrect for panel with glass facings.

(1/m)	-Log(A)	m	A
0.061771	0.015143	16.18879	0.9657

Epoxy / R=0.1 Curve Fits

σ_o =	182548	A =	0.9657
ε_o =	1.21	m =	16.19

ZOLTEK Coupon	R-Value	Maximum Stress PSI	Minimum stress PSI	Frequency Hz	0.1 - 0.3% Modulus** (msi)	Maximum Strain %	cycles to failure	thickness (mm)	VF
2429-0214	static		-190852	0.5"/sec	17.89	-1.0668	1	3.023	0.564
2429-0203	static		-185396	0.5"/sec	17.89	-1.0363	1	3.048	0.559
2429-0217	static		-171395	0.5"/sec	17.89	-0.9580	1	3.251	0.524
2429-0205	-1	110000	-110000	1	17.89	0.6100	751	3.073	0.554
2429-0213	-1	90000	-90000	2	17.89	0.5000	23349	3.061	0.557
2429-0212	-1	80000	-80000	2	17.89	0.4440	1200000	3.150	0.541
2429-0201	-1	110000	-110000	1	17.89	0.6100	413	2.832	0.602
2429-0208	-1	110000	-110000	1	17.89	0.6100	2097	3.175	0.537
2429-0210	-1	90000	-90000	2	17.89	0.5000	55857	3.226	0.528
2429-0218	-1	80000	-80000	2	17.89	0.4440	617787	3.239	0.526

Updated Modulus / Strain Calculation

Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$	Calculated s-N Curve N	σ (%)	Calculated N
15.1	1.264	0.00	1.045	-0.01932	1	176292	1
15.1	1.228	0.00	1.016	-0.00672	10	152919	10
15.1	1.135	0.00	0.939	0.02738	100	132645	100
15.1	0.728	2.88	0.603	0.21998	1000	115059	1000
15.1	0.596	4.37	0.493	0.30713	10000	99804	10000
15.1	0.530	6.08	0.438	0.35829	100000	86572	100000
15.1	0.728	2.62	0.603	0.21998	1000000	75094	1000000
15.1	0.728	3.32	0.603	0.21998	10000000	65138	10000000
15.1	0.596	4.75	0.493	0.30713			
15.1	0.530	5.79	0.438	0.35829			

MATERIAL "P2B" from DOE/MSU Database
Lay-up = (±45/08C/ 45), Newport carbon NB307-D1 prepreg 0 , 300/m2 with glass 0/90 prepreg for ±45 , 298 g/m2

(1/m)	-Log(A)	m	A
0.038471	0.00082	25.99394	0.9981

Epoxy / R=-1 Curve Fits

σ_o =	1047.0	A =	0.9981
ε_o =	1.08	m =	25.99

* Intec-measured values for modulus used in "updated" calculations.

Updated Modulus / Strain Calculation

coupon	Max Stress MPa	R-value	Frequency Hz	Modulus GPa	Strain %	Cycles	comments R=runout	Modulus* Gpa	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$
P2B-210	-1079 *		13	96.7	-1.06	1		95.91	1.116	0.00	1.031	-0.01322
P2B-211	-1062 *		13	96.7	-1.04	1		95.91	1.098	0.00	1.014	-0.00599
P2B-580	-1052 *		13	96.7	-1.03	1		95.91	1.088	0.00	1.005	-0.00220
P2B-579	-1022 *		13	96.7	-1.00	1		95.91	1.057	0.00	0.976	0.01038
P2B-584	-1070 *		13	96.7	-1.05	1		95.91	1.106	0.00	1.022	-0.00940
P2B-740	-1002 *		13	96.7	-0.98	1		95.91	1.037	0.00	0.957	0.01887
P2B-741	-1025 *		13	96.7	-1.00	1		95.91	1.060	0.00	0.979	0.00930
P2B-742	-1039 *		13	96.7	-1.02	1		95.91	1.074	0.00	0.992	0.00344
P2B-743	-1189 *		13	96.7	-1.17	1		95.91	1.229	0.00	1.136	-0.05520
P2B-744	-1113 *		13	96.7	-1.09	1		95.91	1.151	0.00	1.064	-0.02675
P2B-745	-962 *		13	96.7	-0.94	1		95.91	0.995	0.00	0.919	0.03669
P2B-746	-1069 *		13	96.7	-1.05	1		95.91	1.105	0.00	1.021	-0.00891
P2B-747	-1069 *		13	96.7	-1.05	1		95.91	1.106	0.00	1.021	-0.00914
P2B-748	-983 *		13	96.7	-0.96	1		95.91	1.017	0.00	0.939	0.02724
P2B-749	-1069 *		13	96.7	-1.05	1		95.91	1.106	0.00	1.021	-0.00911
P2B-750	-1090 *		13	96.7	-1.07	1		95.91	1.127	0.00	1.041	-0.01738
P2B-751	-958 *		13	96.7	-0.94	1		95.91	0.991	0.00	0.915	0.03852
P2B-752	-1003 *		13	96.7	-0.98	1		95.91	1.037	0.00	0.958	0.01877
P2B-753	-1036 *		13	96.7	-1.02	1		95.91	1.071	0.00	0.989	0.00465
P2B-208	517	-1	2	96.7	-0.51	2000000	25 R	95.91	0.535	6.30	0.494	0.30634
P2B-221	690	-1	2	96.7	-0.68	104909		95.91	0.713	5.02	0.659	0.18141
P2B-300	793	-1	1	96.7	-0.78	1362		95.91	0.820	3.13	0.757	0.12071
P2B-313	793	-1	1	96.7	-0.78	329		95.91	0.820	2.52	0.757	0.12071
P2B-306	793	-1	1	96.7	-0.78	9862		95.91	0.820	3.99	0.757	0.12071
P2B-309	793	-1	1	96.7	-0.78	3160		95.91	0.820	3.50	0.757	0.12071
P2B-309A	690	-1	2	96.7	-0.68	273100		95.91	0.713	5.44	0.659	0.18141
P2B-303A	690	-1	2	96.7	-0.68	739691		95.91	0.713	5.87	0.659	0.18141
P2B-310	586	-1	3	96.7	-0.57	739284		95.91	0.606	5.87	0.560	0.25199
P2B-581	621	-1	3	96.7	-0.61	367170		95.91	0.642	5.56	0.593	0.22716
P2B-592	621	-1	2	96.7	-0.61	1116740		95.91	0.642	6.05	0.593	0.22716
P2B-305A	827	-1	1	96.7	-0.81	152		95.91	0.856	2.18	0.790	0.10222
P2B-215	827	-1	1	96.7	-0.81	73		95.91	0.856	1.86	0.790	0.10222
P2B-301	827	-1	1	96.7	-0.81	5231		95.91	0.856	3.72	0.790	0.10222
P2B-325	827	-1	1	96.7	-0.81	409		95.91	0.856	2.61	0.790	0.10222
P2BX-110	621	-1	1	96.7	-0.61	643945		95.91	0.642	5.81	0.593	0.22716
P2B-270	621	-1	1	96.7	-0.61	235636		95.91	0.642	5.37	0.593	0.22716
P2BX-108	724	-1	1	96.7	-0.71	13033		95.91	0.749	4.12	0.691	0.16022
P2B-508	724	-1	1	96.7	-0.71	21138		95.91	0.749	4.33	0.691	0.16022

Calculated σ-N Curve		Calculated ε-N Curve	
N	σ (%)	N	ε (%)
1	1045.0	1	1.081
10	956.4	10	0.989
100	875.3	100	0.905
1000	801.1	1000	0.828
10000	733.2	10000	0.758
100000	671.1	100000	0.694
1000000	614.2	1000000	0.635
10000000	562.1	10000000	0.581

GEC I.D. SN5-022X
SAERTEX Carbon-Glass Triax / Epoxy

(1/m)	-Log(A)	m	A
0.033071	0.002023	30.2378	0.9954

* Intec-measured values for modulus used in "updated" calculations.

Epoxy / R=0.1 Curve Fits

σ_o =	1297.0	A =	0.9954
ε_o =	1.68	m =	30.24

Coupon	Resin	Lab	Type	Stress ksi	Stress MPa	Strain	Freq. (Hz)	Cycles	Tabs?
2369-0101	Epoxy	Intec	Tensile	194.0	1336.7	1.65%		1	Yes
2369-0111	Epoxy	Intec	Tensile	186.0	1281.5	1.58%		1	Yes
2369-0106	Epoxy	Intec	Tensile	192.0	1322.9	1.63%		1	Yes
2369-0112	Epoxy	Intec	Tensile	181.0	1247.1	1.53%		1	Yes
H	Epoxy	MSU	0.1	120.0	826.8	1.05%	2	85911	No
A	Epoxy	MSU	0.1	130.0	895.7	1.13%	2	23925	No
B	Epoxy	MSU	0.1	130.0	895.7	1.13%	2	141744	No
F	Epoxy	MSU	0.1	120.0	826.8	1.05%	2	49126	No
L	Epoxy	MSU	0.1	120.0	826.8	1.05%	1	60350	No
T	Epoxy	MSU	0.1	120.0	826.8	1.05%	2	84392	No
M	Epoxy	MSU	0.1	120.0	826.8	1.05%	2	687166	No
S	Epoxy	MSU	0.1	120.0	826.8	1.05%	3	1624423	No
U	Epoxy	MSU	0.1	140.0	964.6	1.21%	3	903287	No
P	Epoxy	MSU	0.1	160.0	1102.4	1.37%	1	228	No
J	Epoxy	MSU	0.1	160.0	1102.4	1.37%	1	382	No
D	Epoxy	MSU	0.1	140.0	964.6	1.21%	2	27807	No
N	Epoxy	MSU	0.1	140.0	964.6	1.21%	1	7390	No

Updated Modulus / Strain Calculation

Modulus* Gpa	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$	Calculated σ-N Curve N	Calculated σ-N Curve σ (%)	Calculated ε-N Curve N	Calculated ε-N Curve ε (%)
77.4	1.727	0.00	1.031	-0.01307	1	1291.0	1	1.668
77.4	1.656	0.00	0.988	0.00522	10	1196.4	10	1.546
77.4	1.709	0.00	1.020	-0.00857	100	1108.6	100	1.432
77.4	1.611	0.00	0.961	0.01706	1000	1027.3	1000	1.327
77.4	1.068	4.93	0.637	0.19555	10000	952.0	10000	1.230
77.4	1.157	4.38	0.691	0.16079	100000	882.2	100000	1.140
77.4	1.157	5.15	0.691	0.16079	1000000	817.5	1000000	1.056
77.4	1.068	4.69	0.637	0.19555	10000000	757.6	10000000	0.979
77.4	1.068	4.78	0.637	0.19555				
77.4	1.068	4.93	0.637	0.19555				
77.4	1.068	5.84	0.637	0.19555				
77.4	1.068	6.21	0.637	0.19555				
77.4	1.246	5.96	0.744	0.12861				
77.4	1.424	2.36	0.850	0.07062				
77.4	1.424	2.58	0.850	0.07062				
77.4	1.246	4.44	0.744	0.12861				
77.4	1.246	3.87	0.744	0.12861				

GEC I.D. SN5-0262
SAERTEX Carbon-Glass Triax / VE Resin (with MSU post-cure)

(1/m)	-Log(A)	m	A
0.059395	6.06E-05	16.83645	0.9999

* Intec-measured values for modulus used in "updated" calculations.

VE / R=0.1 Curve Fits

σ_o =	1330.8	A =	0.9999
ε_o =	1.68	m =	16.84

Coupon	Resin	Lab	Type	Stress ksi	Stress MPa	Strain	Freq. (Hz)	Cycles	Tabs?
523	VE	MSU	Tensile	196.2	1352.0	1.68		1	Yes
519	VE	MSU	Tensile	195.1	1344.4	1.54		1	Yes
520	VE	MSU	Tensile	188.1	1296.0	1.6		1	Yes
501	VE	MSU	0.1	130.0	895.7	1.09	2	659	Yes
509	VE	MSU	0.1	120.0	826.8	1.03	2	2422	Yes
507	VE	MSU	0.1	100.0	689.0	0.85	2	3972	Yes
511	VE	MSU	0.1	95.0	654.6	0.82	2	93425	Yes
512	VE	MSU	0.1	110.0	757.9	1.08	2	7163	Yes
510	VE	MSU	0.1	100.0	689.0	0.95	2	70823	Yes
505	VE	MSU	0.1	95.0	654.6	0.85	2	162290	Yes
518	VE	MSU	0.1	100.0	689.0	0.77	1	28361	Yes
508	VE	MSU	0.1	90.0	620.1	0.78	2	1800000	Yes
500	VE	MSU	0.1	130.0	895.7	1.07	1	1012	Yes
513	VE	MSU	0.1	160.0	1102.4	1.3	1	432	Yes
502	VE	MSU	0.1	120.0	826.8	0.97	1	3971	Yes

Updated Modulus / Strain Calculation

Modulus* Gpa	Maximum Strain	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$	Calculated s-N Curve N	Calculated s-N Curve σ (%)	Calculated e-N Curve N	Calculated e-N Curve ε (%)
79.3	1.705	0.00	1.016	-0.00686	1	1330.6	1	1.678
79.3	1.695	0.00	1.010	-0.00442	10	1160.6	10	1.464
79.3	1.634	0.00	0.974	0.01150	100	1012.2	100	1.276
79.3	1.130	2.82	0.673	0.17196	1000	882.8	1000	1.113
79.3	1.043	3.38	0.621	0.20672	10000	770.0	10000	0.971
79.3	0.869	3.60	0.518	0.28590	100000	671.6	100000	0.847
79.3	0.825	4.97	0.492	0.30818	1000000	585.7	1000000	0.739
79.3	0.956	3.86	0.569	0.24451	10000000	510.9	10000000	0.644
79.3	0.869	4.85	0.518	0.28590				
79.3	0.825	5.21	0.492	0.30818				
79.3	0.869	4.45	0.518	0.28590				
79.3	0.782	6.26	0.466	0.33166				
79.3	1.130	3.01	0.673	0.17196				
79.3	1.390	2.64	0.828	0.08178				
79.3	1.043	3.60	0.621	0.20672				

GEC I.D. SN5-022X
SAERTEX Carbon-Glass Triax / Epoxy

(1/m)	-Log(A)	m	A
0.039832	-0.001269	25.10549	1.0029

* Intec-measured values for modulus used in "updated" calculations.

Epoxy / R= 10 Curve Fits

Updated Modulus / Strain Calculation

σ_o =	859.9	A =	1.0029
ε_o =	1.22	m =	25.11

Coupon	Resin	Lab	Type	Stress ksi	Stress MPa	Strain	Freq. (Hz)	Cycles	Tabs?
2395-0208	Epoxy	Intec	Comp.	122.5	844.0	1.20%		1	Yes
2395-0233	Epoxy	Intec	Comp.	131.8	908.1	1.30%		1	Yes
2395-0234	Epoxy	Intec	Comp.	126.4	870.9	1.20%		1	Yes
401	Epoxy	MSU	Comp.	128.7	886.7	1.40%		1	Yes
402	Epoxy	MSU	Comp.	127.8	880.5	1.39%		1	Yes
403	Epoxy	MSU	Comp.	124.8	859.9	1.35%		1	Yes
2395-0210	Epoxy	MSU	Comp.	123.8	853.0	1.44%		1	Yes
2395-0209	Epoxy	MSU	Comp.	118.9	819.2	1.29%		1	Yes
2395-0217	Epoxy	MSU	10	70.0	482.3	0.68%	5	1066584	Yes
2395-0218	Epoxy	MSU	10	90.0	620.1	0.92%	2	11203	Yes
2395-0219	Epoxy	MSU	10	90.0	620.1	0.92%	2	9397	Yes
2395-0216	Epoxy	MSU	10	80.0	551.2	0.80%	2	122792	Yes
2395-0220	Epoxy	MSU	10	80.0	551.2	0.80%	2	41934	Yes
2395-0230	Epoxy	MSU	10	70.0	482.3	0.68%	3	1455131	Yes
2395-0232	Epoxy	MSU	10	100.0	689.0	1.04%	1	213	Yes

Modulus* Gpa	Maximum Strain	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$	Calculated σ-N Curve N	Calculated σ-N Curve σ (%)	Calculated ε-N Curve N	Calculated ε-N Curve ε (%)
70.3	1.201	0.00	0.982	0.00808	1	862.4	1	1.227
70.3	1.292	0.00	1.056	-0.02370	10	786.8	10	1.119
70.3	1.239	0.00	1.013	-0.00553	100	717.9	100	1.021
70.3	1.261	0.00	1.031	-0.01336	1000	654.9	1000	0.932
70.3	1.253	0.00	1.024	-0.01032	10000	597.6	10000	0.850
70.3	1.223	0.00	1.000	0.00000	100000	545.2	100000	0.776
70.3	1.213	0.00	0.992	0.00349	1000000	497.4	1000000	0.708
70.3	1.165	0.00	0.953	0.02103	10000000	453.8	10000000	0.646
70.3	0.686	6.03	0.561	0.25112				
70.3	0.882	4.05	0.721	0.14197				
70.3	0.882	3.97	0.721	0.14197				
70.3	0.784	5.09	0.641	0.19312				
70.3	0.784	4.62	0.641	0.19312				
70.3	0.686	6.16	0.561	0.25112				
70.3	0.980	2.33	0.801	0.09621				

GEC I.D. SN5-0262
SAERTEX Carbon-Glass Triax / VE Resin (with MSU post-cure)

(1/m)	-Log(A)	m	A
0.035927	0.028816	27.83395	0.9358

* Intec-measured values for modulus used in "updated" calculations.

VE / R= 10 Curve Fits

Updated Modulus / Strain Calculation

σ_o =	965.4	A =	0.9358
ε_o =	1.22	m =	27.83

Coupon	Resin	Lab	Type	Stress ksi	Stress MPa	Strain	Freq. (Hz)	Cycles	Tabs?
546	VE	MSU	Comp.	140.1	965.6	1.20%		1	Yes
565	VE	MSU	Comp.	135.6	934.2	1.10%		1	Yes
566	VE	MSU	Comp.	144.6	996.4	1.24%		1	Yes
586	VE	MSU	10	80.0	551.2	-0.69%	3	471493	Yes
579	VE	MSU	10	90.0	620.1	-0.77%	3	18567	Yes
580	VE	MSU	10	100.0	689.0	-0.86%	1	884	Yes
571	VE	MSU	10	100.0	689.0	-0.86%	1	147	Yes
578	VE	MSU	10	100.0	689.0	-0.86%	1	283	Yes
582	VE	MSU	10	90.0	620.1	-0.77%	2	247807	Yes
575	VE	MSU	10	90.0	620.1	-0.77%	3	313925	Yes
570	VE	MSU	10	80.0	551.2	-0.69%	2	801628	Yes
551	VE	MSU	10	110.0	757.9	-0.95%	1	7	Yes

Modulus* Gpa	Maximum Strain	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$	Calculated σ-N Curve N	Calculated σ-N Curve σ (%)	Calculated ε-N Curve N	Calculated ε-N Curve ε (%)	VE versus Epoxy σ	VE versus Epoxy ε
79.3	1.218	0.00	1.000	-0.00009	1	903.4	1	1.139	4.8%	-7.1%
79.3	1.178	0.00	0.968	0.01426	10	831.7	10	1.049	5.7%	-6.3%
79.3	1.256	0.00	1.032	-0.01372	100	765.7	100	0.966	6.7%	-5.4%
79.3	0.695	5.67	0.571	0.24340	1000	704.9	1000	0.889	7.6%	-4.6%
79.3	0.782	4.27	0.642	0.19225	10000	648.9	10000	0.818	8.6%	-3.7%
79.3	0.869	2.95	0.714	0.14649	100000	597.4	100000	0.753	9.6%	-2.9%
79.3	0.869	2.17	0.714	0.14649	1000000	550.0	1000000	0.694	10.6%	-2.0%
79.3	0.869	2.45	0.714	0.14649	10000000	506.3	10000000	0.638	11.6%	-1.1%
79.3	0.782	5.39	0.642	0.19225						
79.3	0.782	5.50	0.642	0.19225						
79.3	0.695	5.90	0.571	0.24340						
79.3	0.956	0.85	0.785	0.10510						

GEC I.D. SN5-022X
SAERTEX Carbon-Glass Triax / Epoxy

(1/m)	-Log(A)	m	A
0.063217	0.006751	15.81852	0.9846

* Intec-measured values for modulus used in "updated" calculations.

Epoxy / R= -1 Curve Fits

σ_o =	859.9	A =	0.9846
ε_o =	1.22	m =	15.82

Updated Modulus / Strain Calculation

Coupon	Resin	Lab	Type	Stress ksi	Stress MPa	Strain	Freq. (Hz)	Cycles	Tabs?
2395-0208	Epoxy	Intec	Comp.	122.5	844.0	1.20%		1	Yes
2395-0233	Epoxy	Intec	Comp.	131.8	908.1	1.30%		1	Yes
2395-0234	Epoxy	Intec	Comp.	126.4	870.9	1.20%		1	Yes
401	Epoxy	MSU	Comp.	128.7	886.7	1.40%		1	Yes
402	Epoxy	MSU	Comp.	127.8	880.5	1.39%		1	Yes
403	Epoxy	MSU	Comp.	124.8	859.9	1.35%		1	Yes
2395-0210	Epoxy	MSU	Comp.	123.8	853.0	1.44%		1	Yes
2395-0209	Epoxy	MSU	Comp.	118.9	819.2	1.29%		1	Yes
2395-0211	Epoxy	MSU	-1	50.0	344.5	0.46%	3	3562005	Yes
2395-0212	Epoxy	MSU	-1	50.0	344.5	0.46%	3	2613724	Yes
2395-0213	Epoxy	MSU	-1	80.0	551.2	0.70%	1	343	Yes
2395-0214	Epoxy	MSU	-1	65.0	447.9	0.58%	1	14827	Yes
2395-0215	Epoxy	MSU	-1	60.0	413.4	0.54%	2	35949	Yes
2395-0231	Epoxy	MSU	-1	80.0	551.2	0.70%	1	628	Yes

Modulus* Gpa	Maximum Strain	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$	Calculated σ-N Curve N	Calculated σ-N Curve σ (%)	Calculated ε-N Curve N	Calculated ε-N Curve ε (%)
70.3	1.201	0.00	0.982	0.00808	1	846.6	1	1.204
70.3	1.292	0.00	1.056	-0.02370	10	731.9	10	1.041
70.3	1.239	0.00	1.013	-0.00553	100	632.8	100	0.900
70.3	1.261	0.00	1.031	-0.01336	1000	547.1	1000	0.778
70.3	1.253	0.00	1.024	-0.01032	10000	472.9	10000	0.673
70.3	1.223	0.00	1.000	0.00000	100000	408.9	100000	0.582
70.3	1.213	0.00	0.992	0.00349	1000000	353.5	1000000	0.503
70.3	1.165	0.00	0.953	0.02103	10000000	305.6	10000000	0.435
70.3	0.490	6.55	0.401	0.39724				
70.3	0.490	6.42	0.401	0.39724				
70.3	0.784	2.54	0.641	0.19312				
70.3	0.637	4.17	0.521	0.28330				
70.3	0.588	4.56	0.481	0.31806				
70.3	0.784	2.80	0.641	0.19312				

GEC I.D. SN5-0262
SAERTEX Carbon-Glass Triax / VE Resin (with MSU post-cure)

(1/m)	-Log(A)	m	A
0.076449	0.021217	13.08056	0.9523

* Intec-measured values for modulus used in "updated" calculations.

VE / R= -1 Curve Fits

σ_o =	965.4	A =	0.9523
ε_o =	1.22	m =	13.08

Updated Modulus / Strain Calculation

Coupon	Resin	Lab	Type	Stress ksi	Stress MPa	Strain	Freq. (Hz)	Cycles	Tabs?
546	VE	MSU	Comp.	140.1	965.6	1.20%		1	Yes
565	VE	MSU	Comp.	135.6	934.2	1.10%		1	Yes
566	VE	MSU	Comp.	144.6	996.4	1.24%		1	Yes
653	VE	MSU	-1	80.0	551.2	0.69%	1	93	Yes
612	VE	MSU	-1	80.0	551.2	0.69%	1	786	Yes
573	VE	MSU	-1	80.0	551.2	0.69%	1	915	Yes
585	VE	MSU	-1	80.0	551.2	0.69%	1	685	Yes
667	VE	MSU	-1	50.0	344.5	0.43%	2	507295	Yes
670	VE	MSU	-1	60.0	413.4	0.52%	2	21469	Yes
655	VE	MSU	-1	60.0	413.4	0.52%	2	14730	Yes
661	VE	MSU	-1	50.0	344.5	0.43%	2	1464755	Yes

Modulus* Gpa	Maximum Strain	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$	Calculated σ-N Curve N	Calculated σ-N Curve σ (%)	Calculated ε-N Curve N	Calculated ε-N Curve ε (%)	VE versus Epoxy σ	VE versus Epoxy ε
79.3	1.218	0.00	1.000	-0.00009	1	919.4	1	1.159	8.6%	-3.7%
79.3	1.178	0.00	0.968	0.01426	10	771.0	10	0.972	5.3%	-6.6%
79.3	1.256	0.00	1.032	-0.01372	100	646.5	100	0.815	2.2%	-9.4%
79.3	0.695	1.97	0.571	0.24340	1000	542.2	1000	0.684	-0.9%	-12.1%
79.3	0.695	2.90	0.571	0.24340	10000	454.7	10000	0.573	-3.9%	-14.8%
79.3	0.695	2.96	0.571	0.24340	100000	381.3	100000	0.481	-6.8%	-17.3%
79.3	0.695	2.84	0.571	0.24340	1000000	319.7	1000000	0.403	-9.5%	-19.8%
79.3	0.434	5.71	0.357	0.44752	10000000	268.1	10000000	0.338	-12.3%	-22.2%
79.3	0.521	4.33	0.428	0.36834						
79.3	0.521	4.17	0.428	0.36834						
79.3	0.434	6.17	0.357	0.44752						

GEC I.D. SN5-432X
Newport (Grafil) Carbon Prepreg, with straight ply drop

(1/m)	-Log(A)	m	A
0.081991	-0.052532	12.19649	1.1286

* MSU-measured values for modulus used in "updated" calculations.

Updated Modulus / Strain Calculation

Epoxy / R=0.1 Curve Fits

σ_o =	109597	A =	1.1286
ε_o =	0.78	m =	12.20

"Thick Side" Max. Stress (psi)	Strain (%)	R	Cycles for 0.25 inch delam.	Notes	Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-\text{Log}(\sigma/\sigma_o)$	Calculated σ-N Curve N	σ (%)	Calculated ε-N Curve N	ε (%)
109596.8	0.78 *		1		14.00	0.783	0.00	1.000	0.00000	1	123689	1	0.883
60000	0.43 *		22844		14.00	0.429	4.36	0.547	0.26165	10	102409	10	0.731
45000	0.32	0.1	300000		14.00	0.321	5.48	0.411	0.38659	100	84791	100	0.606
35000	0.25	0.1	1252120	run out	14.00	0.250	6.10	0.319	0.49573	1000	70203	1000	0.501
35000	0.25	0.1	2221308		14.00	0.250	6.35	0.319	0.49573	10000	58126	10000	0.415
45000	0.32	0.1	241558		14.00	0.321	5.38	0.411	0.38659	100000	48126	100000	0.344
45000	0.32	0.1	140000		14.00	0.321	5.15	0.411	0.38659	1000000	39846	1000000	0.285
70000	0.50	0.1	2800		14.00	0.500	3.45	0.639	0.19470	10000000	32991	10000000	0.236
75000	0.54	0.1	2100		14.00	0.536	3.32	0.684	0.16474				

GEC I.D. SN5-431X
Newport (Grafil) Carbon Prepreg, with "pinked" ply drop

(1/m)	-Log(A)	m	A
0.056534	-0.024824	17.68841	1.0588

* MSU-measured values for modulus used in "updated" calculations.

Updated Modulus / Strain Calculation

Epoxy / R=0.1 Curve Fits

σ_o =	140128	A =	1.0588
ε_o =	1.24	m =	17.69

"Thick Side" Max. Stress (psi)	Strain (%)	Freq. (Hz)	R	Cycles for 0.25 inch delam.	Notes	Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-\text{Log}(\sigma/\sigma_o)$	Calculated σ-N Curve N	σ (%)	Calculated ε-N Curve N	ε (%)
136794	1.21	0.005 *		1	no delam prior to failure	11.30	1.211	0.00	0.976	0.01046	1	148371	1	1.314
143462	1.27	0.005 *		1	no delam prior to failure	11.30	1.270	0.00	1.024	-0.01021	10	130261	10	1.153
110000	0.97	1	0.1	1800		11.30	0.974	3.26	0.785	0.10513	100	114362	100	1.012
110000	0.97	1	0.1	1300		11.30	0.974	3.11	0.785	0.10513	1000	100403	1000	0.889
90000	0.77	2	0.1	15000		11.30	0.797	4.18	0.642	0.19228	10000	88148	10000	0.780
75000	0.69	3	0.1	85000		11.30	0.664	4.93	0.535	0.27146	100000	77389	100000	0.685
60000	0.53	4	0.1	1100000		11.30	0.531	6.04	0.428	0.36837	1000000	67943	1000000	0.602
											10000000	59650	10000000	0.528

all delaminations started at the point or valley on the pinked plys

GEC I.D. SN5-421X
SAERTEX Carbon-Glass Triax / Epoxy, "straight" ply drop

(1/m)	-Log(A)	m	A
0.09024	0.04289	11.08162	0.9060

* MSU-measured values for modulus used in "updated" calculations.

coupon	maximum stress psi	minimum stress psi	R value	frequency or rate inch/sec	Thickness thin inches	Thickness thick inches	E thin msi	E thick msi	absolute maximum strain, %	cycles for full width delam.	
SN5-421-101	144830	*		0.005	0.2575	0.324			1.24	1	
SN5-421-108	136250	*		0.005	0.2635	0.325	11.348	11.756	1.17	1	
SN5-421-114	148670	*		0.005	0.259	0.331			1.27	1	
SN5-421-100	80000	8000	0.1	1	0.261	0.333			0.721	156	
SN5-421-107	80000	8000	0.1	1	0.258	0.324			0.721	12	
SN5-421-110	80000	8000	0.1	1	0.2615	0.3318			0.721	289	
SN5-421-116	80000	8000	0.1	1	0.258	0.324			0.721	92	
SN5-421-109	65000	6500	0.1	2	0.259	0.326			0.594	2800	
SN5-421-106	65000	6500	0.1	2	0.267	0.332			0.594	513	
SN5-421-103	65000	6500	0.1	2	0.264	0.3295			0.594	4800	
SN5-421-115	50000	5000	0.1	3	0.265	0.3323	11.496	11.888	0.463	256922	
SN5-421-121	50000	5000	0.1	3	0.253	0.326			0.463	84000	
SN5-421-122	50000	5000	0.1	3	0.271	0.322			0.463	49000	
SN5-421-105	40000	4000	0.1	2.5	0.2605	0.328			0.373	74000	
SN5-421-112	40000	4000	0.1	3	0.263	0.332			0.373	880000	
SN5-421-118	40000	4000	0.1	3	0.2575	0.322			0.373	341130	
SN5-421-104	35000	3500	0.1	4	0.259	0.3285			0.328	1500000	full delam
SN5-421-102	35000	3500	0.1	4.5	0.2578	0.3258	12.429	11.714	0.328	1500000	no delam
SN5-421-113	35000	3500	0.1	4	0.264	0.331			0.328	260000	
					Average modulus =		11.76	11.79			

Updated Modulus / Strain Calculation

Epoxy, Straight R=0.1 Curve Fits

σ_o =	143250	A =	0.9060
ε_o =	1.22	m =	11.08

coupon	Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$
SN5-421-101	11.76	1.232	0.000	1.011	-0.00476
SN5-421-108	11.76	1.159	0.000	0.951	0.02176
SN5-421-114	11.76	1.264	0.000	1.038	-0.01613
SN5-421-100	11.76	0.680	2.193	0.558	0.25300
SN5-421-107	11.76	0.680	1.079	0.558	0.25300
SN5-421-110	11.76	0.680	2.461	0.558	0.25300
SN5-421-116	11.76	0.680	1.964	0.558	0.25300
SN5-421-109	11.76	0.553	3.447	0.454	0.34318
SN5-421-106	11.76	0.553	2.710	0.454	0.34318
SN5-421-103	11.76	0.553	3.681	0.454	0.34318
SN5-421-115	11.76	0.425	5.410	0.349	0.45712
SN5-421-121	11.76	0.425	4.924	0.349	0.45712
SN5-421-122	11.76	0.425	4.690	0.349	0.45712
SN5-421-105	11.76	0.340	4.869	0.279	0.55403
SN5-421-112	11.76	0.340	5.944	0.279	0.55403
SN5-421-118	11.76	0.340	5.533	0.279	0.55403
SN5-421-104	11.76	0.298	6.176	0.244	0.61203
SN5-421-102	11.76	0.298	6.176	0.244	0.61203

Calculated s-N Curve N	Calculated s-N Curve σ (%)	Calculated e-N Curve N	Calculated e-N Curve ε (%)
1	129779	1	1.104
10	105430	10	0.897
100	85650	100	0.728
1000	69580	1000	0.592
10000	56526	10000	0.481
100000	45921	100000	0.390
1000000	37305	1000000	0.317
10000000	30306	10000000	0.258

GEC I.D. SN5-423X
SAERTEX Carbon-Glass Triax / Epoxy, "pinked" ply drop

(1/m)	-Log(A)	m	A
0.104121	-0.001131	9.604254	1.0026

* MSU-measured values for modulus used in "updated" calculations.

coupon	maximum stress psi	minimum stress psi	R value	frequency or rate inch/sec	Thickness thin inches	Thickness thick inches	E thin msi	E thick msi	absolute maximum strain, %	cycles for full width delam.	
SN5-423-114	175228	*		0.005	0.2635	0.3275			1.48	1	
SN5-423-115	183203	*		0.005	0.2575	0.328			1.54	1	
SN5-423-112	177998	*		0.005	0.2545	0.3265			1.5	1	
SN5-423-119	120000	12000	0.1	1	0.25	0.316	11.68	12.11	1.05	92	
SN5-423-100	100000	10000	0.1	1	0.2665	0.328			0.886	650	
SN5-423-105	100000	10000	0.1	1	0.262	0.325			0.886	102	
SN5-423-102	100000	10000	0.1	1	0.261	0.334			0.886	167	
SN5-423-113	80000	8000	0.1	2	0.263	0.332			0.721	4200	
SN5-423-109	80000	8000	0.1	2	0.27	0.335			0.721	4800	
SN5-423-106	80000	8000	0.1	2	0.262	0.322			0.721	6000	
SN5-423-111	65000	6500	0.1	2	0.253	0.315			0.594	8000	
SN5-423-104	65000	6500	0.1	2	0.259	0.326			0.594	17000	
SN5-423-112	65000	6500	0.1	2	0.262	0.32			0.594	26000	
SN5-423-101	50000	5000	0.1	2	0.269	0.326			0.463	132000	
SN5-423-103	50000	5000	0.1	2.5	0.255	0.321			0.463	210000	
SN5-423-117	50000	5000	0.1	3	0.2573	0.3258			0.463	31000	
SN5-423-112	40000	4000	0.1	4	0.26	0.328			0.373	2120000	just started to delam
SN5-423-110	40000	4000	0.1	5	0.256	0.32			0.373	2500000	70% cracked
					Average modulus =		11.68	12.11			

Updated Modulus / Strain Calculation

Epoxy, Pinked R=0.1 Curve Fits

σ_o =	178810	A =	1.0026
ε_o =	1.53	m =	9.60

coupon	Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-Log(\sigma/\sigma_o)$
SN5-423-114	11.68	1.500	0.000	0.980	0.00879
SN5-423-115	11.68	1.569	0.000	1.025	-0.01054
SN5-423-112	11.68	1.524	0.000	0.995	0.00198
SN5-423-119	11.68	1.027	1.964	0.671	0.17321
SN5-423-100	11.68	0.856	2.813	0.559	0.25239
SN5-423-105	11.68	0.856	2.009	0.559	0.25239
SN5-423-102	11.68	0.856	2.223	0.559	0.25239
SN5-423-113	11.68	0.685	3.623	0.447	0.34930
SN5-423-109	11.68	0.685	3.681	0.447	0.34930
SN5-423-106	11.68	0.685	3.778	0.447	0.34930
SN5-423-111	11.68	0.557	3.903	0.364	0.43948
SN5-423-104	11.68	0.557	4.230	0.364	0.43948
SN5-423-112	11.68	0.557	4.415	0.364	0.43948
SN5-423-101	11.68	0.428	5.121	0.280	0.55342
SN5-423-103	11.68	0.428	5.322	0.280	0.55342
SN5-423-117	11.68	0.428	4.491	0.280	0.55342
SN5-423-112	11.68	0.342	6.326	0.224	0.65033
SN5-423-110	11.68	0.342	6.398	0.224	0.65033

Calculated s-N Curve N	Calculated s-N Curve σ (%)	Calculated e-N Curve N	Calculated e-N Curve ε (%)
1	179276	1	1.535
10	141059	10	1.208
100	110989	100	0.950
1000	87329	1000	0.748
10000	68713	10000	0.588
100000	54065	100000	0.463
1000000	42540	1000000	0.364
10000000	33472	10000000	0.287

GEC I.D. SN5-422X
SAERTEX Carbon-Glass Triax / VE, "straight" ply drop

* MSU-measured values for modulus used in "updated" calculations.

coupon	maximum stress psi	minimum stress psi	R value	frequency or rate inch/sec	Thickness thin inches	Thickness thick inches	E thin msi	E thick msi	absolute maximum strain, %	cycles for full width delam.	delam strain
SN5-422-105	162783	*		0.005	0.273	0.338	12.11	12.46	1.39	1	1.16
SN5-422-102	161001	*		0.005	0.276	0.348	10.69	10.86	1.37	1	0.96
SN5-422-103	160622	*		0.005	0.266	0.336	11.93	11.93	1.37	1	1.1
SN5-422-111	80000	8000	0.1	2	0.27	0.3385			0.721	252	
SN5-422-120	80000	8000	0.1	2	0.274	0.3385			0.721	62	
SN5-422-131	80000	8000	0.1	2	0.2565	0.31			0.721	1050	
SN5-422-119	65000	6500	0.1	3	0.2755	0.339			0.594	427	
SN5-422-118	65000	6500	0.1	3	0.272	0.333			0.594	890	
SN5-422-130	65000	6500	0.1	3	0.2455	0.31			0.594	8300	
SN5-422-106	50000	5000	0.1	2	0.267	0.3405			0.463	45000	
SN5-422-117	50000	5000	0.1	3	0.269	0.339			0.463	9100	
SN5-422-114	50000	5000	0.1	3	0.27	0.343			0.463	17000	
SN5-422-113	40000	4000	0.1	3	0.267	0.3365			0.373	220000	
SN5-422-107	40000	4000	0.1	3	0.278	0.341			0.373	260000	
SN5-422-108	35000	3500	0.1	4	0.266	0.336			0.328	1100000	
SN5-422-112	35000	3500	0.1	4	0.267	0.338			0.328	300000	
SN5-422-109	30000	3000	0.1	5	0.268	0.3365			0.282	1700000	no delam
SN5-422-110	30000	3000	0.1	5	0.275	0.3435			0.282	3000000	no delam
					Average modulus =		11.58	11.75			

(1/m)	-Log(A)	m	A
0.110113	0.029069	9.081603	0.9353

VE, Straight R=0.1 Curve Fits

σ_o =	161469	A =	0.9353
ε_o =	1.39	m =	9.08

Updated Modulus / Strain Calculation

Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-\text{Log}(\sigma/\sigma_o)$	Calculated s-N Curve N	Calculated s-N Curve σ (%)	Calculated e-N Curve N	Calculated e-N Curve ε (%)
11.58	1.406	0.000	1.008	-0.00352	1	151015	1	1.304
11.58	1.390	0.000	0.997	0.00126	10	117194	10	1.012
11.58	1.387	0.000	0.995	0.00228	100	90948	100	0.785
11.58	0.691	2.401	0.495	0.30500	1000	70580	1000	0.609
11.58	0.691	1.792	0.495	0.30500	10000	54773	10000	0.473
11.58	0.691	3.021	0.495	0.30500	100000	42507	100000	0.367
11.58	0.561	2.630	0.403	0.39517	1000000	32987	1000000	0.285
11.58	0.561	2.949	0.403	0.39517	10000000	25599	10000000	0.221
11.58	0.561	3.919	0.403	0.39517				
11.58	0.432	4.653	0.310	0.50912				
11.58	0.432	3.959	0.310	0.50912				
11.58	0.432	4.230	0.310	0.50912				
11.58	0.345	5.342	0.248	0.60603				
11.58	0.345	5.415	0.248	0.60603				
11.58	0.302	6.041	0.217	0.66402				
11.58	0.302	5.477	0.217	0.66402				
11.58	0.259	6.230	0.186	0.73097				
11.58	0.259	6.477	0.186	0.73097				

GEC I.D. SN5-424X
SAERTEX Carbon-Glass Triax / VE, "pinked" ply drop

* MSU-measured values for modulus used in "updated" calculations.

coupon	maximum stress psi	minimum stress psi	R value	frequency or rate inch/sec	Thickness thin inches	Thickness thick inches	E thin msi	E thick msi	absolute maximum strain, %	cycles for full width delam.	
SN5-424-104	163768	*		0.005	0.261	0.33			1.37817	1	
SN5-424-103	166371	*		0.005	0.262	0.343			1.400076	1	
SN5-424-111	166697	*		0.005	0.261	0.334			1.402819	1	
SN5-424-105	120000	12000	0.1	1	0.273	0.3455			1.045	180	
SN5-424-122	120000	12000	0.1	1	0.241	0.32	11.32	11	1.05	1200	
SN5-424-106	100000	10000	0.1	1.5	0.2655	0.3265			0.886	921	
SN5-424-112	100000	10000	0.1	1	0.264	1.007			0.886	400	
SN5-424-119	100000	10000	0.1	2	0.265	0.33			0.89	1600	
SN5-424-110	80000	8000	0.1	1	0.2765	0.345			0.721	3800	
SN5-424-118	80000	8000	0.1	2	0.2765	0.34			0.72	9000	
SN5-424-107	80000	8000	0.1	1.5	0.259	0.323			0.721	2500	
SN5-424-117	65000	6500	0.1	2	0.277	0.347	11.81	12.9	0.594	120000	
SN5-424-120	65000	6500	0.1	2	0.267	0.333			0.594	30000	
SN5-424-116	65000	6500	0.1	2	0.275	0.342			0.594	160000	
SN5-424-109	50000	5000	0.1	2	0.255	0.324			0.463	310000	
SN5-424-108	50000	5000	0.1	2	0.265	0.329			0.463	130000	
SN5-424-113	50000	5000	0.1	2	0.262	0.33			0.46	375000	
SN5-424-114	40000	4000	0.1	5	0.27	0.342			0.373	1500000	delam 75%
SN5-424-115	40000	4000	0.1	4	0.272	0.332			0.37	650000	
					Average modulus =		11.57	11.95			

(1/m)	-Log(A)	m	A
0.098302	-0.041211	10.17278	1.0995

VE, Pinked R=0.1 Curve Fits

σ_o =	165612	A =	1.0995
ε_o =	1.43	m =	10.17

Updated Modulus / Strain Calculation

Modulus* (msi)	Maximum Strain (abs, %)	Log(N)	σ/σ_o	$-\text{Log}(\sigma/\sigma_o)$	Calculated s-N Curve N	Calculated s-N Curve σ (%)	Calculated e-N Curve N	Calculated e-N Curve ε (%)
11.57	1.415	0.000	0.989	0.00486	1	182097	1	1.574
11.57	1.438	0.000	1.005	-0.00199	10	145212	10	1.255
11.57	1.441	0.000	1.007	-0.00284	100	115798	100	1.001
11.57	1.037	2.255	0.725	0.13991	1000	92342	1000	0.798
11.57	1.037	3.079	0.725	0.13991	10000	73637	10000	0.636
11.57	0.864	2.964	0.604	0.21909	100000	58721	100000	0.508
11.57	0.864	2.602	0.604	0.21909	1000000	46827	1000000	0.405
11.57	0.864	3.204	0.604	0.21909	10000000	37342	10000000	0.323
11.57	0.691	3.580	0.483	0.31600				
11.57	0.691	3.954	0.483	0.31600				
11.57	0.691	3.398	0.483	0.31600				
11.57	0.562	5.079	0.392	0.40618				
11.57	0.562	4.477	0.392	0.40618				
11.57	0.562	5.204	0.392	0.40618				
11.57	0.432	5.491	0.302	0.52012				
11.57	0.432	5.114	0.302	0.52012				
11.57	0.432	5.574	0.302	0.52012				
11.57	0.346	6.176	0.242	0.61703				
11.57	0.346	5.813	0.242	0.61703				

Mosty Glass - Last Ply Out
One Ply Transition

THIN SIDE HAS CARBON

SN5-332X

(1/m)	-Log(A)	m	A
0.07249	-0.00074	13.79499	1.0017

Mostly Carbon - 2 Plys / R=0.1 Curve Fits

σ_o =	118799	A =	1.0017
ε_o =	2.33	m =	13.79

	STRESS THIN	THICK	R	CYCLES	THIN	THICK	MODULUS THIN	MODULUS THICK	notes
	psi	psi			% strain	% strain	msi	msi	
GEC G300	118736	110076 *		1	2.21	2.53	5.366	4.352	
GEC G308	118502	110322 *		1	2.34	2.45	5.064	4.4957	
GEC G311	119159	110382 *		1	2.43	2.49	4.888	4.437	
GEC G306	40000	37167	0.1	950000	0.804	0.75	4.87	4.45	0.185" DELAM AT RUNOUT
GEC G307	50000	46153	0.1	150000	1.01	0.93	5	4.44	DELAM
GEC G304	60000	55507	0.1	17000	1.21	1.12	4.93	4.505	DELAM
GEC G301	60000	55986	0.1	8000	1.24	1.16	4.759	4.576	DELAM
GEC G310	80000	74153	0.1	40	1.74	1.61	5.148	4.289	DELAM

Log(N)	$\varepsilon/\varepsilon_o$	$-Log(\varepsilon/\varepsilon_o)$	Calculated σ-N Curve N	σ (%)	Calculated ε-N Curve N	ε (%)
0.000	0.950	0.02234	1	119003	1	2.331
0.000	1.006	-0.00248	10	100709	10	1.972
0.000	1.044	-0.01887	100	85227	100	1.669
5.978	0.346	0.46148	1000	72125	1000	1.413
5.176	0.434	0.36241	10000	61037	10000	1.195
4.230	0.520	0.28395	100000	51654	100000	1.012
3.903	0.533	0.27331	1000000	43714	1000000	0.856
1.602	0.748	0.12618	10000000	36994	10000000	0.725

Mosty Glass - Last Ply Out
Two Ply Transitions

THIN SIDE HAS CARBON

SN5-334X

(1/m)	-Log(A)	m	A
0.102365	0.032727	9.768997	0.9274

Mostly Carbon - 2 Plys / R=0.1 Curve Fits

σ_o =	110725	A =	0.9274
ε_o =	1.94	m =	9.77

	STRESS THIN	THICK	R	CYCLES	THIN	THICK	MODULUS THIN	MODULUS THICK	notes
	psi	psi			% strain	% strain	msi	msi	
GEC G103	105228	98838 *		1	1.8	2.23	5.847	4.439	
GEC G102	119098	112268 *		1	2.09	2.55			
GEC G101	107848	100558 *		1	1.92	2.31	5.603	4.357	
GEC G100	30000	28114	0.1	290000	0.53	0.64	5.683	4.374	DELAM
GEC G109	30000	28060	0.1	180000	0.53	0.64			DELAM
GEC G105	50000	46657	0.1	100	0.899	1.15			DELAM
GEC G111	50000	46613	0.1	400	0.845	1.06	5.675	4.463	DELAM
GEC G110	25000	23515	0.1	1600000	0.44	0.53	5.662	4.41	RUNOUT

Log(N)	$\varepsilon/\varepsilon_o$	$-Log(\varepsilon/\varepsilon_o)$	Calculated σ-N Curve N	σ (%)	Calculated ε-N Curve N	ε (%)
0.000	0.929	0.03178	1	102687	1	1.796
0.000	1.079	-0.03309	10	81125	10	1.419
0.000	0.991	0.00375	100	64090	100	1.121
5.462	0.274	0.56278	1000	50632	1000	0.886
5.255	0.274	0.56278	10000	40000	10000	0.700
2.000	0.464	0.33330	100000	31601	100000	0.553
2.602	0.436	0.36020	1000000	24965	1000000	0.437
6.204	0.227	0.64360	10000000	19723	10000000	0.345

Mosty Carbon - First Ply Out THICK SIDE HAS GLASS
Two Ply Transitions

(1/m)	-Log(A)	m	A
0.04329	-0.00996	23.09981	1.0232

SN5-333X

Mostly Carbon - 2 Plys / R=0.1 Curve Fits

σ_o =	133176	A =	1.0232
ε_o =	0.95	m =	23.10

	STRESS THIN	THICK	R	CYCLES	THIN	THICK	MODULUS THIN	MODULUS THICK	notes
	psi	psi			% strain	% strain	msi	msi	
GEC 810	140748	132204 *		1	1.01	1.07	13.889	12.404	FAILED ACROSS PLY DROP
GEC 804	125603	119178 *		1	0.88	0.91	14.223	13.044	EDGE SPLITTING, GRIP FAILURE
GEC 805	80488	75345	0.1	34765	0.541	0.6			GRIP FAILURE
GEC 801	67073	63393	0.1	2000000	0.5	0.55			RUNOUT
GEC 808	110000	103568	0.1	22000	0.78	0.81			EDGE SPLITTING
GEC 807	95665	90000	0.1	10000	0.68	0.71			RUNOUT
GEC 803	67073	62832	0.1	3000000	0.48	0.49			RUNOUT

Log(N)	$\varepsilon/\varepsilon_o$	$-Log(\varepsilon/\varepsilon_o)$	Calculated σ-N Curve N	σ (%)	Calculated ε-N Curve N	ε (%)
0.000	1.069	-0.02889	1	136264	1	0.967
0.000	0.931	0.03095	10	123336	10	0.875
4.541	0.572	0.24223	100	111635	100	0.792
6.301	0.529	0.27646	1000	101044	1000	0.717
4.342	0.825	0.08334	10000	91458	10000	0.649
4.000	0.720	0.14292	100000	82781	100000	0.587
6.477	0.508	0.29419	1000000	74927	1000000	0.532
			10000000	67819	10000000	0.481

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