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CHARACTERIZATION OF MULTIAXIAL WARP KNIT COMPOSITES

H. Benson Dexter
NASA Langley Research Center
Hampton, Virginia

Gregory H. Hasko
Lockheed Engineering and Science Company
Hampton, Virginia

Roberto J. Cano
NASA Langley Research Center
Hampton, Virginia

INTRODUCTION

Textile reinforced composites with through-the-thickness reinforcement have demonstrated excellent damage tolerance compared to state-of-the-art laminated tape composites, references 1, 2, and 3. The potential for significant cost savings for textile reinforced composites through automated preform fabrication and low-cost, out-of-autoclave resin transfer molding has increased aerospace interest in these materials. Woven fabrics are used extensively in the fabrication of composite aircraft structures. Individual plies of fabric are generally laminated together to produce various combinations of 0/90 and ±45-degree layups. Recently, a relatively new class of fabrics designated as multiaxial warp knits has been developed to minimize some of the drawbacks to woven fabrics. The drawbacks include fiber crimp, limited fiber orientations, and labor intensive layup procedures. The multiaxial warp knit fabrics have minimal fiber crimp, precise fiber orientations (0, 90, $\pm\theta$), and multi-ply stacks can be knitted together to reduce labor costs.

The objectives of this investigation were to characterize the mechanical behavior and damage tolerance of two multiaxial warp knit fabrics and to determine the acceptability of these fabrics for high performance composite applications. The multiaxial warp knit fabrics were produced by Hexcel Hi-Tech and Milliken. The tests performed included compression, tension, open hole compression, open hole tension, compression after impact and compression-compression fatigue. Tests were performed on as-fabricated fabrics and on multilayer fabrics that were stitched together with either carbon or Kevlar stitching yarn. Results of processing studies for vacuum impregnation with Hercules 3501-6 epoxy resin and pressure impregnation with both Dow Tactix 138/H41 epoxy resin and British Petroleum BP E905L epoxy resin are presented.

POTENTIAL AEROSPACE APPLICATIONS OF MULTIAXIAL WARP KNIT FABRICS

The potential aerospace applications of multiaxial warp knit fabrics include broadgoods replacement for biaxial woven fabric, postformed structural shapes, and dimensionally stable sheet stock for pultrusion. The broadgoods that can be produced with multiaxial knitting machines include [0, 90], [$\pm\theta$], [$0 \pm \theta$], [$90 \pm \theta$], and [0, 90, $\pm\theta$] orientations. An example of a postformed structural shape is shown in figure 1. The knitted sine wave beam was formed over forming blocks and the knitted plies were tacked together with a powdered epoxy tackifier.

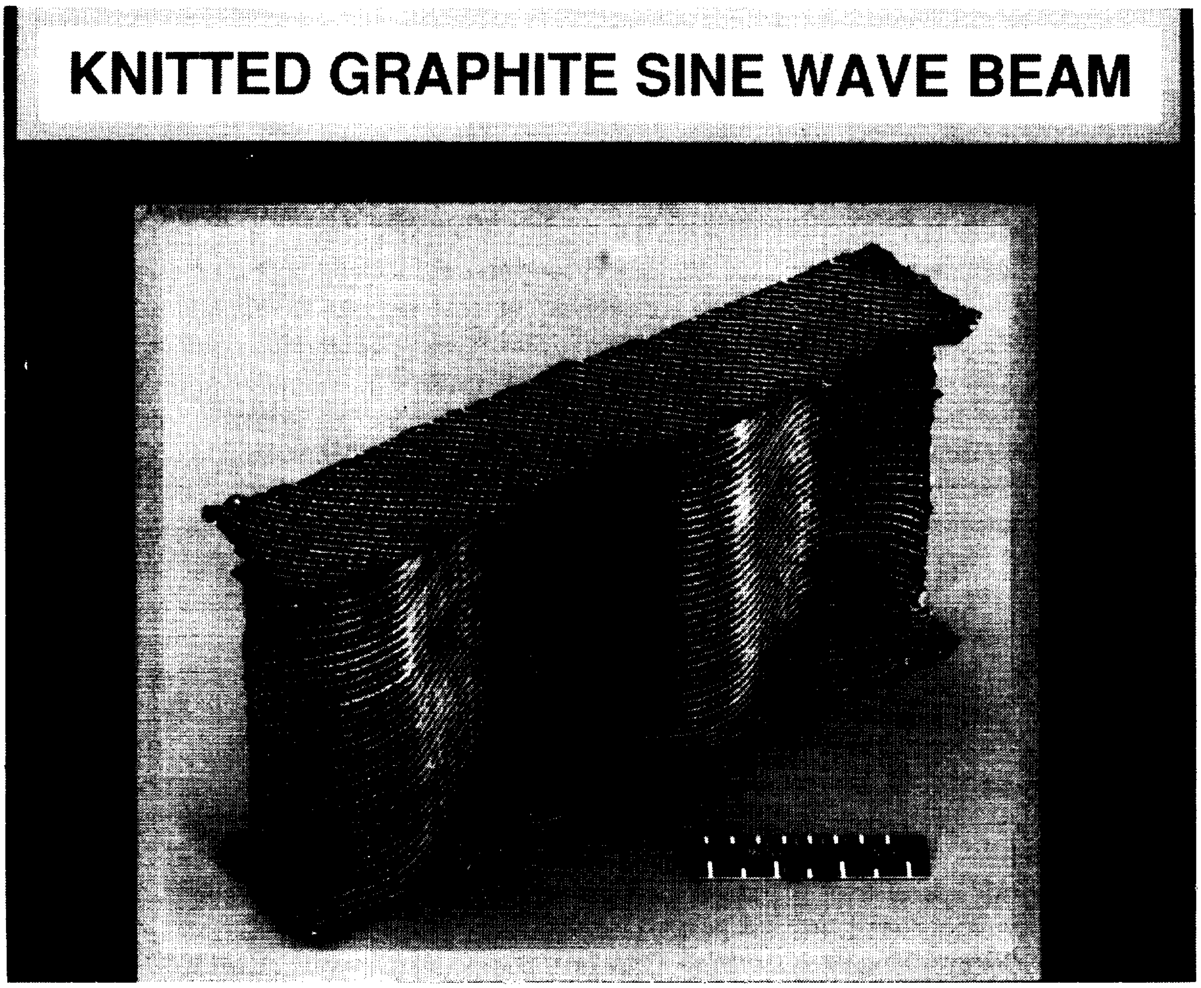

Figure 1

HEXCEL HI-TECH MULTIAXIAL WARP KNITTING MACHINE

The multiaxial warp knit fabric obtained from Hexcel Hi-Tech was fabricated on a machine that was developed by Hexcel Hi-Tech, figure 2. The Hexcel Hi-Tech machine can produce up to an 8-ply fabric with ply orientations of (0, 90, $\pm\theta$), with θ ranging from 30 to 90 degrees. The machine can produce fabrics up to 100-inches wide at a rate of 50 lineal yards/hour. The fabric for this investigation was produced by laying down bands of 6K carbon tows. The 0- and 90-degree plies had 38 tows per band and the $\pm$45-degree plies had 27 tows per band to provide a balanced areal weight. The fabric produced had an average areal weight per ply of 430 g/m^2. The sketch in figure 2 shows that the 90- and $\pm$45-degree tows are laid down by yarn carriers moving along fixed guides. The 0-degree tows are laid down off a beam just prior to the 4-ply stack being knitted together. A chain stitch was used to knit the fabric plies together.

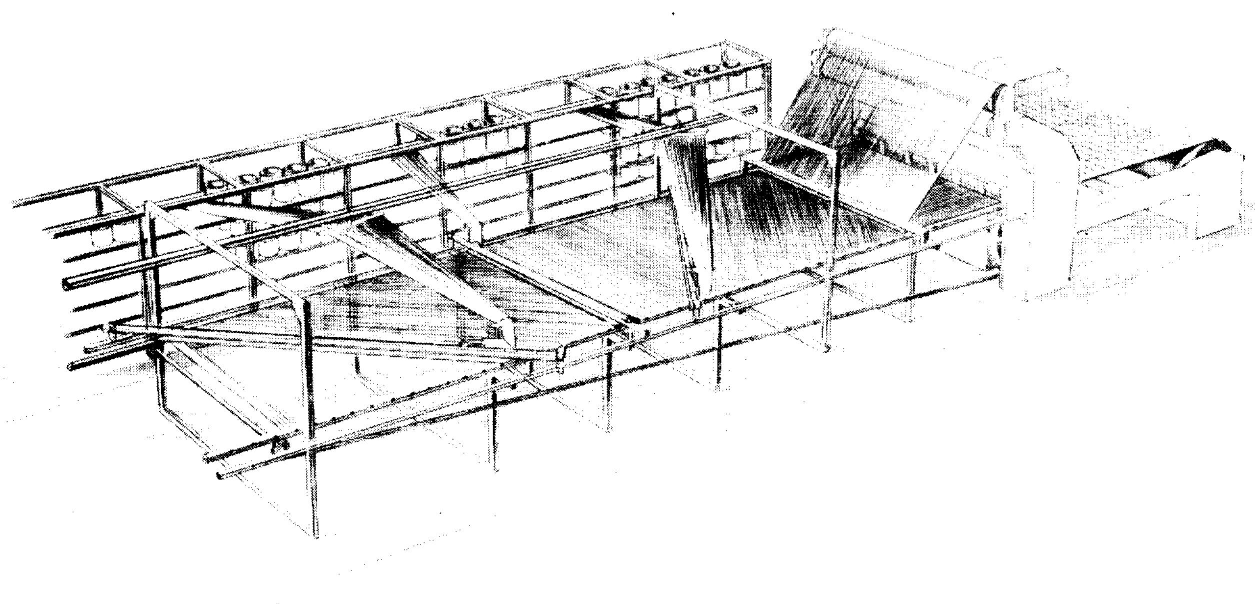

Figure 2

DESCRIPTION OF HEXCEL HI-TECH MULTIAXIAL WARP KNIT FABRIC

Hercules AS-4, 6K epoxy-sized carbon tows were used to produce the fabric. A 16-ply quasi-isotropic $(+45, 0, -45, 90)_{2s}$ fabric preform stack was fabricated by Hexcel Hi-Tech as shown in figure 3. Three knitted ply subgroup patterns were used to build up the required thickness as indicated in the figure. The 3-ply and single-ply subgroups were produced by knitting the carbon tows together with a 70 denier polyester yarn. Eight subgroups were stacked to form the full 16-ply laminate. Some of the 16-ply stacks were stitched together with T-900-1000-50A carbon stitching yarn using a modified lockstitch.

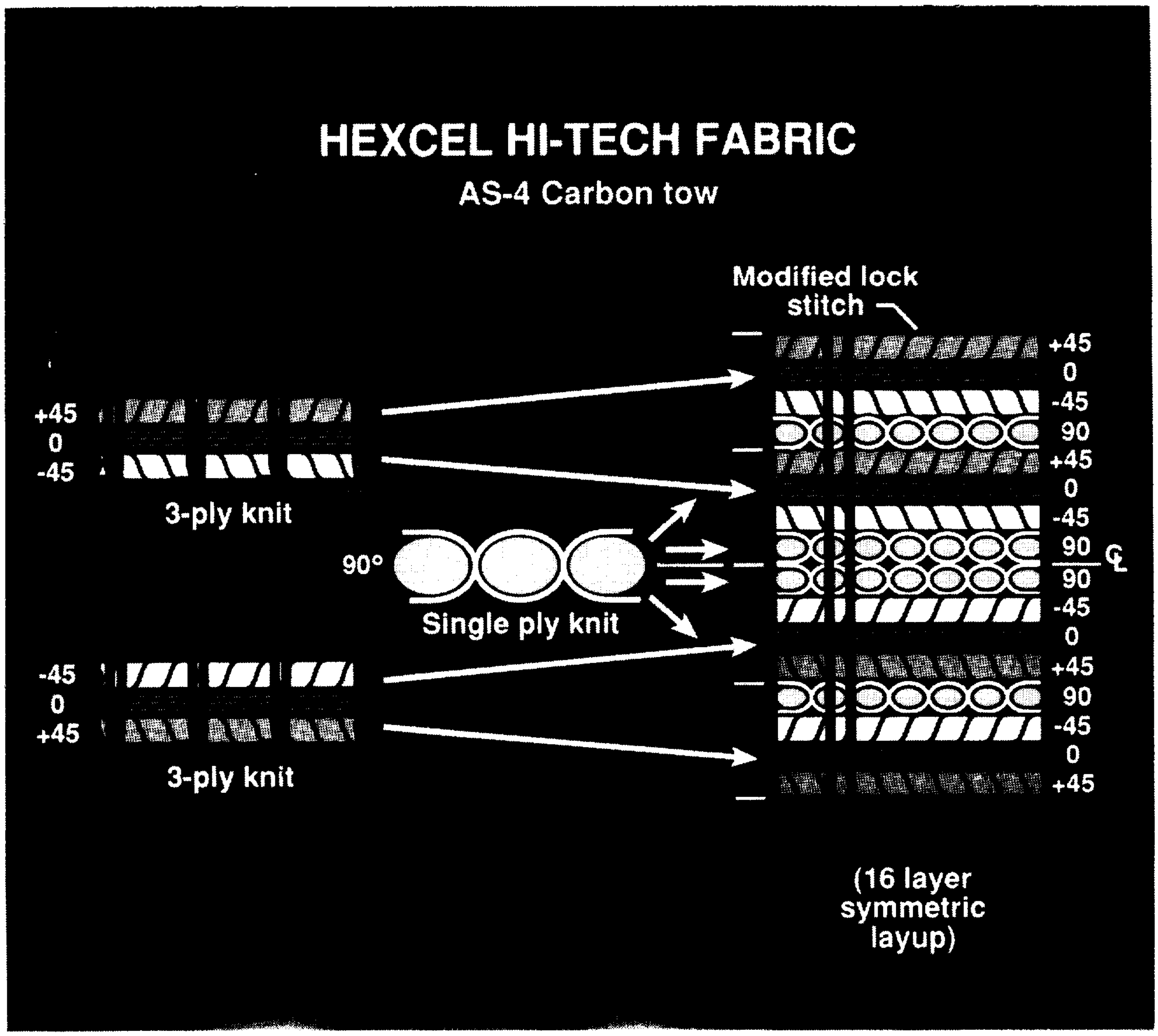

Figure 3

HEXCEL HI-TECH KNITTED AND STITCHED FABRICS

The Hexcel Hi-Tech knitted and knitted/stitched fabrics are shown in figure 4. A 70 denier polyester yarn was used to knit the carbon tows together. A chain stitch was used to knit the individual tows together and a modified lockstitch was used to stitch the 16-ply stack together. The polyester knitting yarns were spaced in rows 1/6-inch apart with a pitch of 9 stitches/inch. The carbon stitching yarns were spaced in rows and columns 1/4-inch apart with a pitch of approximately 8 stitches/inch. The polyester knit yarns pierced the carbon tows and imparted limited damage to some of the tows. The photographs shown in figure 4 indicate only minimal inplane distortion of the carbon tows due to penetration of the polyester knitting yarns. The Toray T-900-1000-50A carbon stitching yarn was much larger in diameter than the polyester knitting yarn, which resulted in additional fiber distortion and damage.

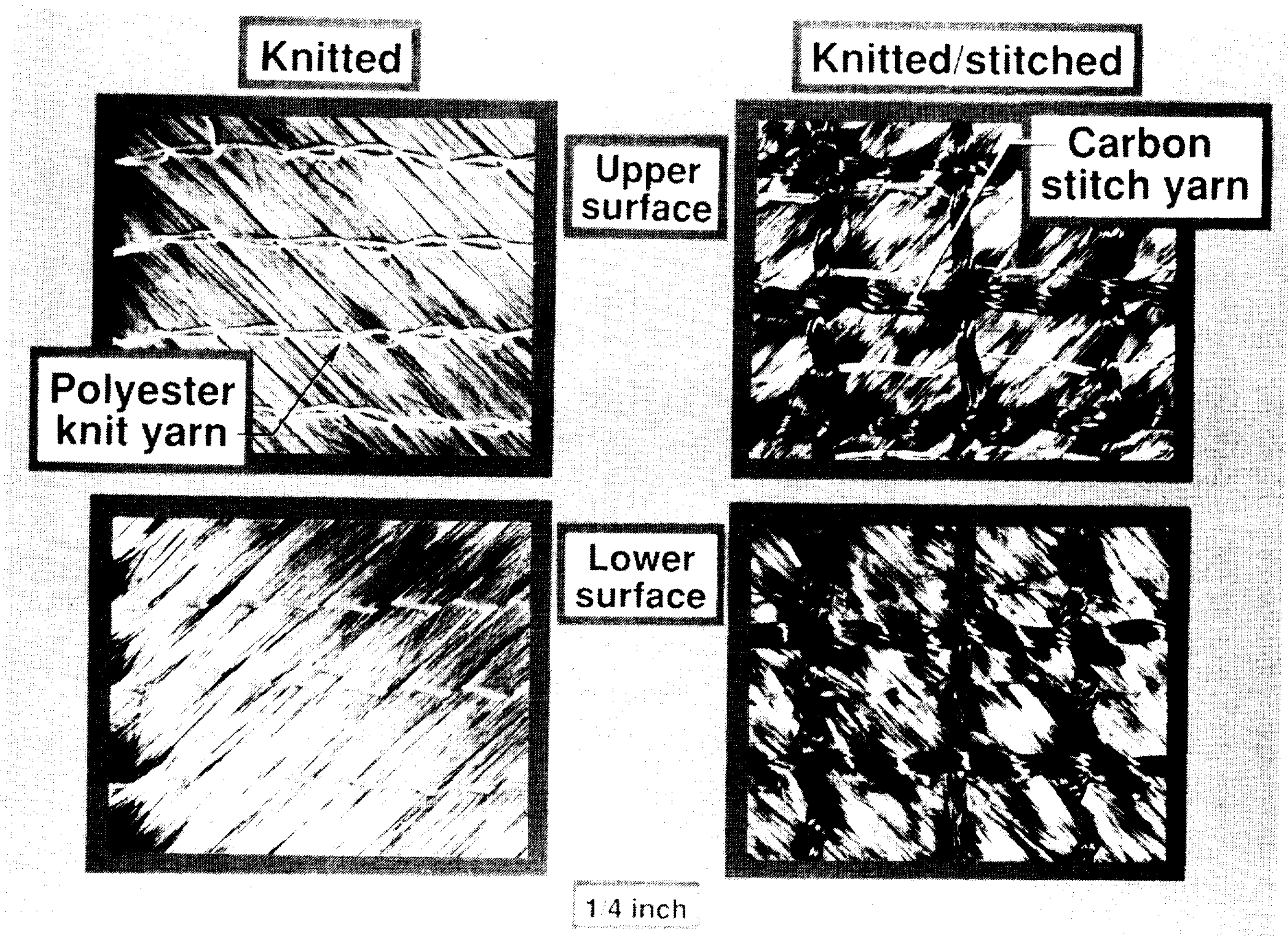

Figure 4

MILLIKEN MULTIAXIAL WARP KNITTING MACHINE

The multiaxial warp knit fabric obtained from Milliken was fabricated on a machine that was manufactured by the Mayer Textile Machine Corporation, figure 5. The Milliken machine can produce a 4-ply fabric with ply orientations of (0, 90, $\pm\theta$), with θ ranging from 30 to 60 degrees. Fabrics with (0, 90), ($0\pm\theta$), ($90\pm\theta$), ($\pm\theta$) and (0, 90, $\pm\theta$) fiber orientations can also be produced with the Milliken machine. In addition, an auxiliary backing material can be included in the knitted fabric. The machine can produce fabrics up to 62 inches wide at a rate of 50 lineal yards/hour. The machine was operated at approximately 30 lineal yards/hour to minimize damage to the carbon tows. The tow count for the fabric produced for this investigation was 12 tows/inch in the warp and fill directions and 17 tows/inch in the $\pm$45-degree directions of the fabric. A chain stitch was used to knit the (−45, +45, 0, 90) plies together. The fabric produced had an average areal weight per ply of 430 g/m^2.

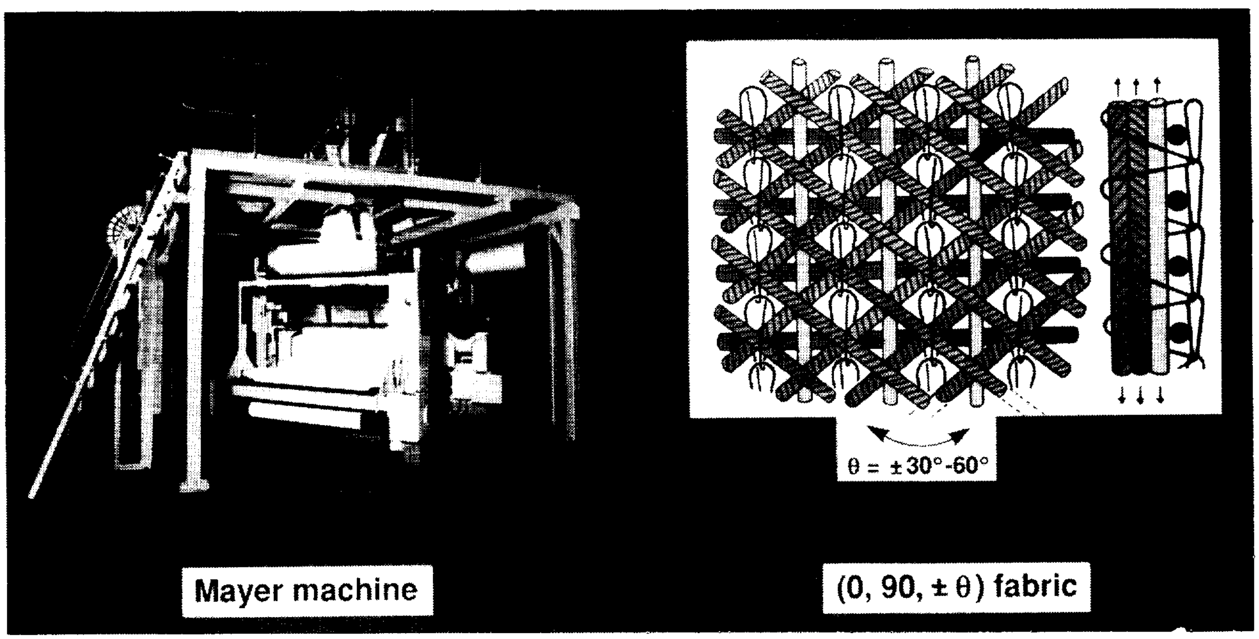

Figure 5

DESCRIPTION OF MILLIKEN MULTIAXIAL WARP KNIT FABRIC

The Milliken fabric was made on the knitting machine discussed in figure 5. The fabric design shown in figure 6 was produced with Hercules AS-4 epoxy-sized carbon tows. The 0- and 90-degree plies were produced with 12K tows, whereas 9K tows were used for the ±45-degree plies. This tow distribution was required to achieve similar ply areal weights because of the different tow count for the off-axis plies. Only the 4-ply subgroup (−45, +45, 0, 90) shown in figure 6 was produced for this investigation. An additional 4-ply subgroup (+45, −45, 0, 90) would be required to produce a symmetric quasi-isotropic fabric preform. Four 4-ply subgroups were stacked to form the full 16-ply laminate. Note that the 16-ply stack shown in figure 6 is unsymmetric. The 4-ply subgroup was produced by knitting the carbon tows together with a polyester yarn. Some of the 16-ply stacks were stitched together with Kevlar 29 1500 denier stitching yarn using a chain stitch.

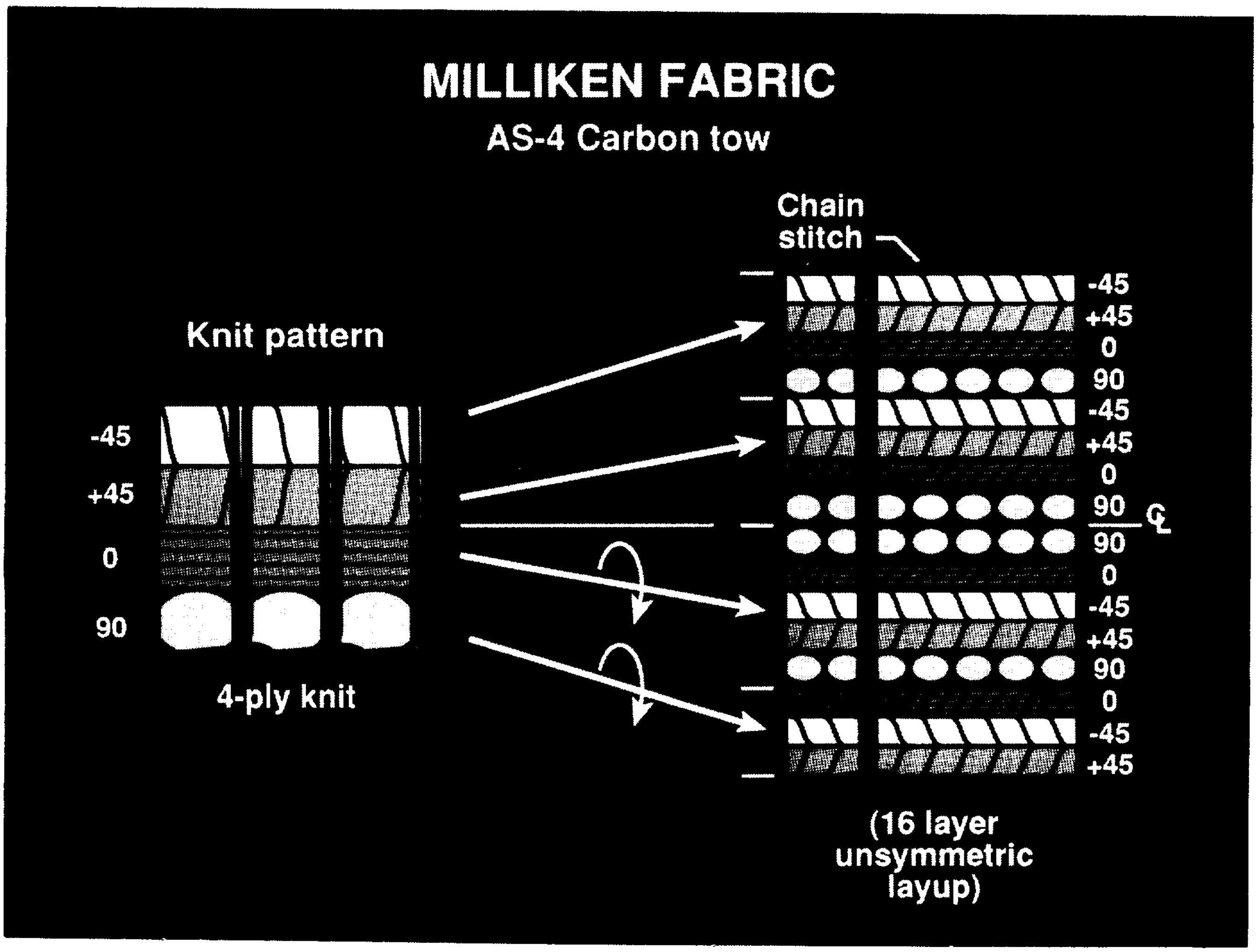

Figure 6

MILLIKEN KNITTED AND STITCHED FABRICS

The Milliken knitted and stitched fabrics are shown in figure 7. A 150 denier polyester yarn was used to knit the carbon tows together. A chain stitch was used to knit the individual tows together and a Kevlar chain stitch was also used to stitch the 16-ply stacks together. The polyester knitting yarns were spaced in rows 1/12-inch apart with a pitch of 12 stitches/in. The Kevlar 29 stitching yarns were spaced in rows and columns 1/4-inch apart with a pitch of approximately 8 stitches/inch. The polyester knit yarns surrounded the individual carbon tows which resulted in a gap of approximately 0.01-inch between the carbon tows. Since the knitting needles did not pierce the carbon tows, minimal damage was imparted to the fabric as a result of the knitting operation. The photographs in figure 7 indicate a high degree of uniformity and yarn straightness in the knitted fabric. The Kevlar 29 1500 denier stitching yarns caused some distortion in the carbon tows, especially at the intersection of the rows and columns.

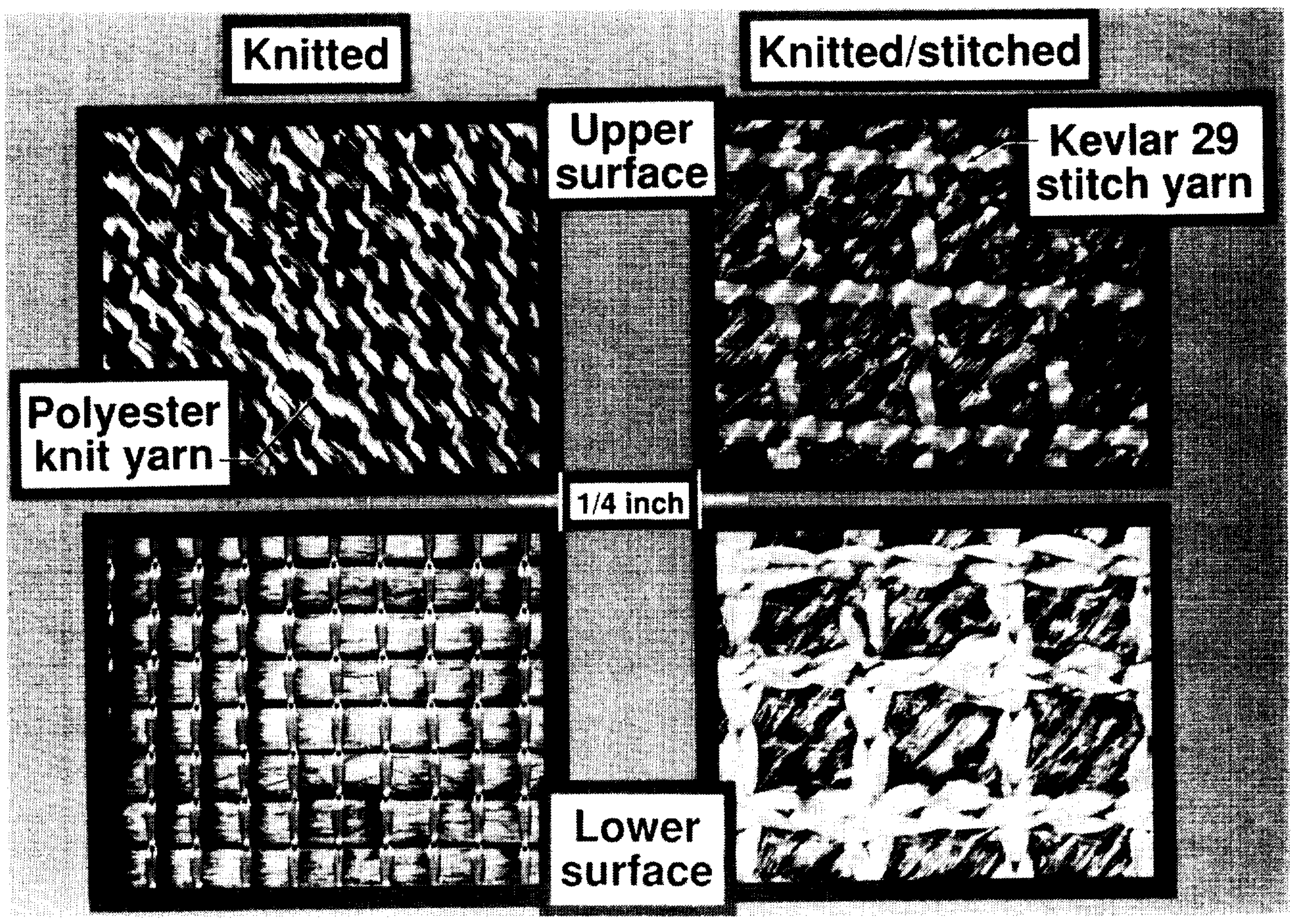

Figure 7

COMPACTION AND PERMEABILITY CHARACTERISTICS OF HEXCEL HI-TECH AS-4 KNITTED/STITCHED FABRIC

The compaction and permeability characteristics of a fabric can be used as an aid in the development of infiltration and cure cycles. As part of a NASA Langley grant, Virginia Polytechnic Institute and State University (VPI & SU) developed experimental techniques to measure fabric compaction and permeability. As shown in figure 8, the fiber volume fraction and fabric thickness is a nonlinear function of compaction pressure. The Hexcel Hi-Tech knitted/stitched fabric had a nominal uncompacted fiber volume fraction of approximately 51 percent and a thickness of approximately 0.310-inch. To achieve a fiber volume fraction of over 62 percent and a final thickness of 0.250-inch, a compaction pressure of approximately 90 psig is required.

Also shown in figure 8 is the effect of fiber volume fraction or permeability. Permeability is a function of fabric architecture, compaction, porosity, and flow direction. Permeability along a fiber bundle can be an order of magnitude greater than transverse to the fiber bundle. Through-the-thickness stitching may increase fabric permeability by providing additional flow paths through the thickness of the fabric. Tightly woven or high fiber volume fraction fabrics would have less porosity and thus be more difficult to infiltrate with resin. The compaction and permeability data generated under the VPI & SU grant were used to generate infiltration and cure cycles for the Hexcel Hi-Tech knitted/stitched fabric and the Milliken knitted fabric.

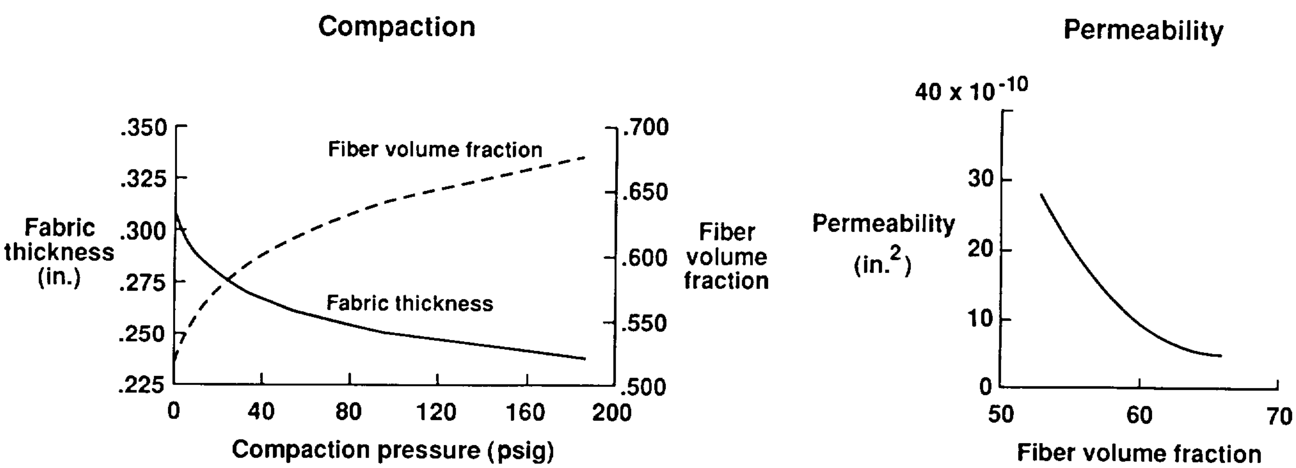

Figure 8

C-3

Three types of resins and associated impregnation processes were used in this investigation. Viscosity profiles and cure cycles used for two of the resins, Hercules 3501-6 and Dow Tactix 138/H41, are shown in figure 9. The 3501-6 resin is a solid at room temperature and was used in a vacuum/pressure process where a resin film was melted and infiltrated through-the-thickness of the fabric. The 3501-6 resin melts during a ramp up to 245°F at which time a minimum viscosity of approximately 500 cps is achieved. The fabric is fully impregnated during the low viscosity window. Full vacuum plus 2 psi of platen pressure is used to impregnate the fabric. Total impregnation is completed within 40 minutes and the platen pressure is increased to 90 psi to insure proper compaction. After a 1-hour hold at 245°F, the temperature is ramped to 350°F and the cure cycle is completed after a 2-hour hold.

The Tactix 138/H41 epoxy resin mixture has a room temperature viscosity of over 1000 cps. To reduce the viscosity, the resin is heated to 150°F for impregnation. The viscosity drops below 200 cps for approximately 1 hour at which time full impregnation occurs. Resin is injected into the mold cavity and fabric under 25 psi pressure and full vacuum to remove entrapped air. The resin exit valve in the RTM tool is closed and the cure cycle is initiated. Temperature is raised to 250°F and held for 1 hour while the resin gels. A mold clamping pressure of 200 psi is applied to close the mold and to achieve the desired laminate thickness. The final cure is completed after a 2-hour hold at 350°F.

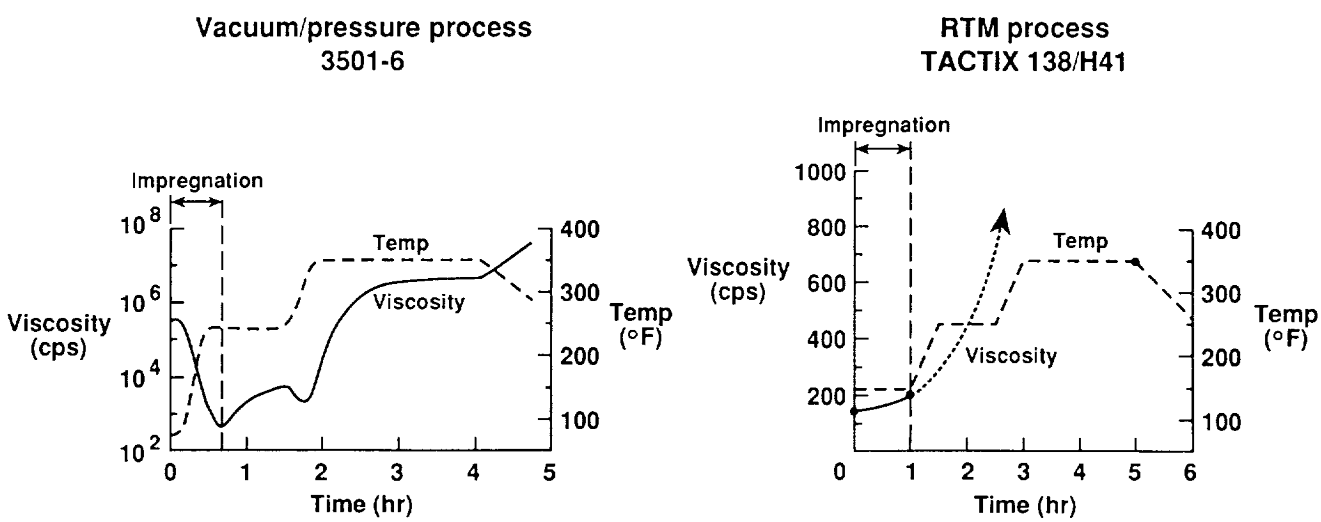

Figure 9

VACUUM/PRESSURE IMPREGNATION PROCESS

The vacuum/pressure impregnation process was used to mold panels with Hercules 3501-6 resin. As shown in figure 10, a resin film is placed in the bottom of the mold and resin flow is in one direction, up through the thickness of the fabric. A vacuum press is used to apply heat and pressure and to evacuate entrapped air. The resin is weighed to give the desired volume fraction, melted, degassed under vacuum, and poured into the mold cavity where it solidifies. The fabric is carefully trimmed to fit the 12-inch by 12-inch cavity size and placed in the mold so that all edges have a slight press fit. This insures that there are no gaps to allow resin to escape around the fabric. A breather layer of porous Teflon-coated fiberglass is placed over the fabric to allow air to escape, but to prevent excessive resin bleed. The caul plate is placed in the mold cavity to apply pressure to the fabric. Pressure must be close to that required to achieve the desired thickness and fiber volume; too much pressure results in a thin panel and too little pressure leads to voids. The caul plate is sized to allow only enough gap for the breather fabric to extend out of the mold. This tight fit allows excess resin to bleed out and provides a path for air venting. The entire mold assembly is placed between heated platens in a vacuum press for the prescribed cure cycle. Since the fabric is not pressed to thickness stops, slight variations in final part thickness may result.

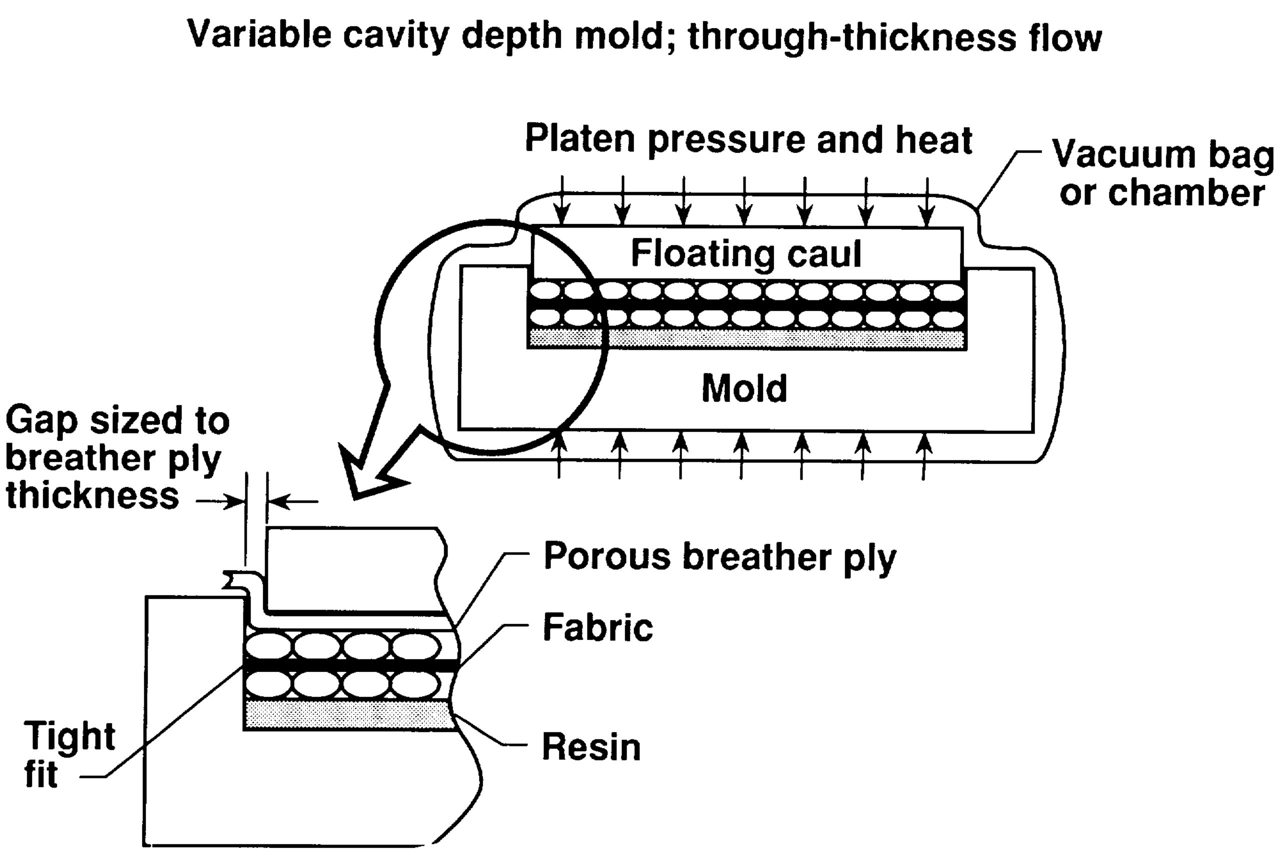

Figure 10

The resin transfer molding (RTM) process shown in figure 11 was developed by Boeing Aerospace under contract to NASA Langley. Panels 11.5-inch by 11.5-inch by 0.250-inch were molded and shipped to NASA Langley for testing. The RTM method is used to mold panels with resins having stable, low viscosities at room or slightly elevated temperature, such as Dow Tactix 138/H41. Resin flow is two-dimensional in the plane of the fabric. As indicated in the figure, an O-ring is used to seal the mold to prevent resin leakage and air entrainment. The mold assembly is placed between two platens in a hydraulic press to close the mold and apply sufficient pressure to debulk the fabric and seat the O-ring. The mold cavity depth is sized to achieve a prescribed fabric thickness and fiber volume fraction.

Resin enters the mold from a pressurized tank and fills a channel around the perimeter of the fabric. Resin flows radially inward through the fabric to an exit port in the center of the mold. A vacuum pump is attached to the exit port to remove excess air. Once the fabric preform is fully infiltrated and air is evacuated, the exit valve is closed and the prescribed cure cycle is followed. Cured panels may have minor thickness variations due to machining tolerances of the mold.

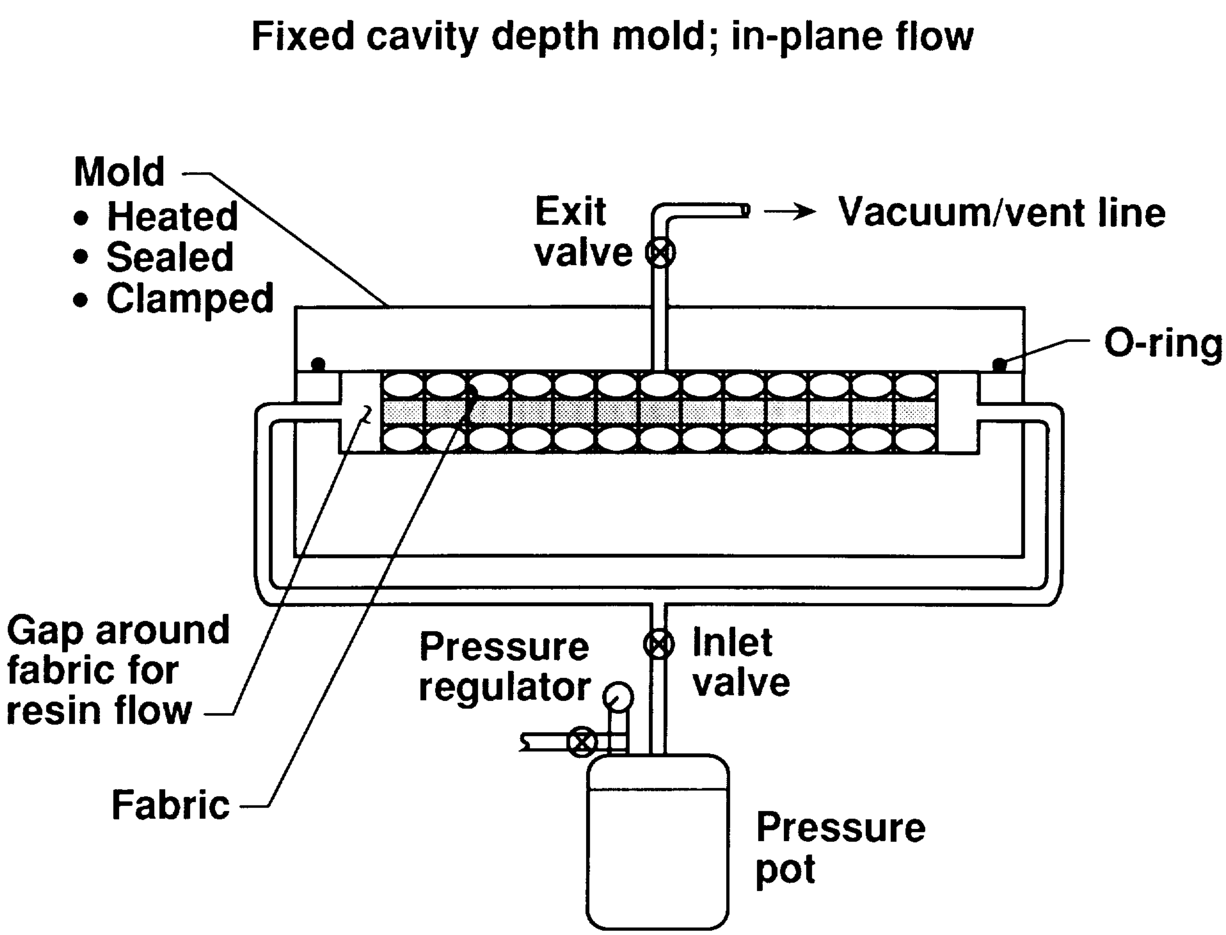

Figure 11

PHOTOMICROGRAPHS OF HEXCEL HI-TECH LAMINATES

Photomicrographs of Hexcel Hi-Tech laminates are shown in figure 12. Good compaction of the plies was achieved as evidenced by the nesting of the 90-degree plies. The well-defined shape of the 90-degree plies at the mid-plane of the knitted laminate is a result of constraint provided by the polyester knitting yarn. As a result, resin-rich areas are evident between the tow bundles. There are two significant characteristics evident in the knitted-stitched laminate shown in figure 12. Large resin-rich areas are evident around the carbon fiber stitching yarns and microcracking is evident throughout the laminate. The microcracking is caused by residual thermal stresses that occur during cool-down of the laminate after the resin is cured. As indicated in figure 12, void-free laminates were produced.

During the course of this investigation several laminates were fabricated by the vacuum/ pressure impregnation method with various levels of compaction pressure. The higher pressures resulted in laminates with higher fiber volume fractions. Fiber volume fractions, determined by acid digestion, ranged from 56 to 63 percent with an average of 59 percent.

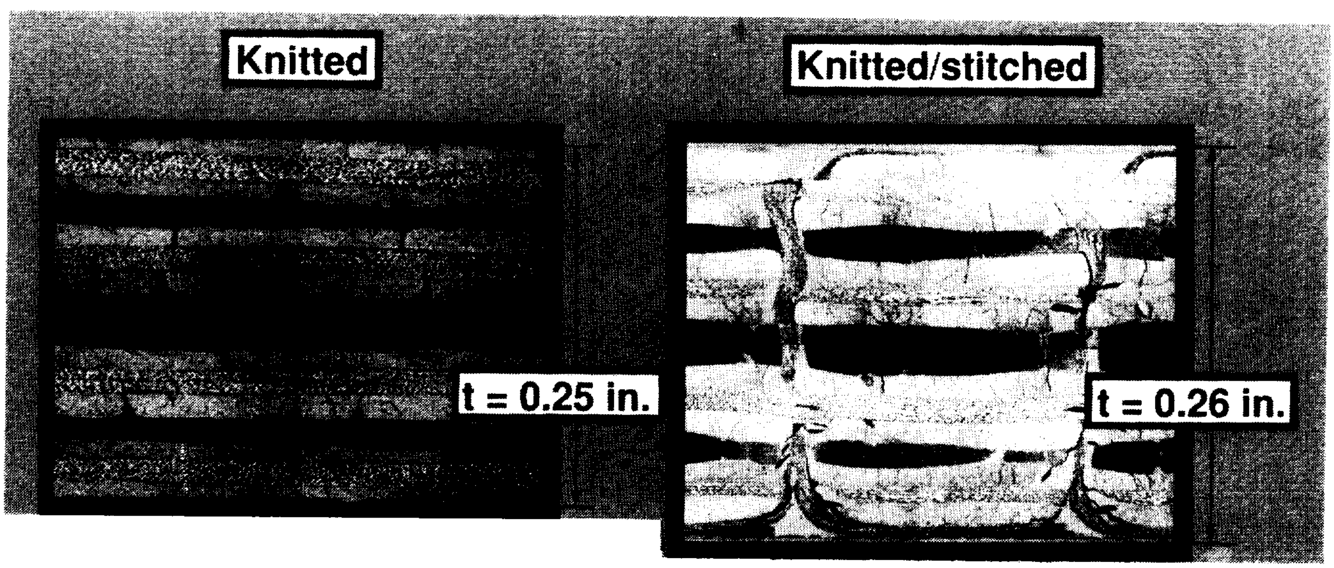

Figure 12

PHOTOMICROGRAPHS OF MILLIKEN LAMINATES

Photomicrographs of Milliken laminates are shown in figure 13. The 150 denier polyester knit yarns used in fabricating the (−45, +45, 0, 90) 4-ply fabric provided excellent stability to the fabric. A high degree of uniformity in carbon tow spacing was achieved. The individual carbon tows could not spread to fill the inherent gaps between the tows. As a result, uniform resin-rich pockets are evident throughout the laminates. The volume fraction of the resin pockets was reduced during the course of this investigation by using less resin and applying higher pressure during the compaction portion of the cure cycle. The first laminate fabricated with a pressure of 45 psi had a thickness of 0.270-inch, whereas the laminates produced with 90 psi pressure had thicknesses ranging from 0.240-inch to 0.250-inch.

Due to limited material availability, only one Kevlar-stitched laminate was fabricated by the vacuum/pressure impregnation process for this investigation. Significant resin-starved areas on the surface and internal porosity were evident for this laminate. Additional fabrication trials are required to optimize the resin impregnation and cure process. The photomicrograph of the Kevlar-stitched laminate shown in figure 13 indicates less microcracking than the Hexcel Hi-Tech carbon-stitched laminate shown in figure 12.

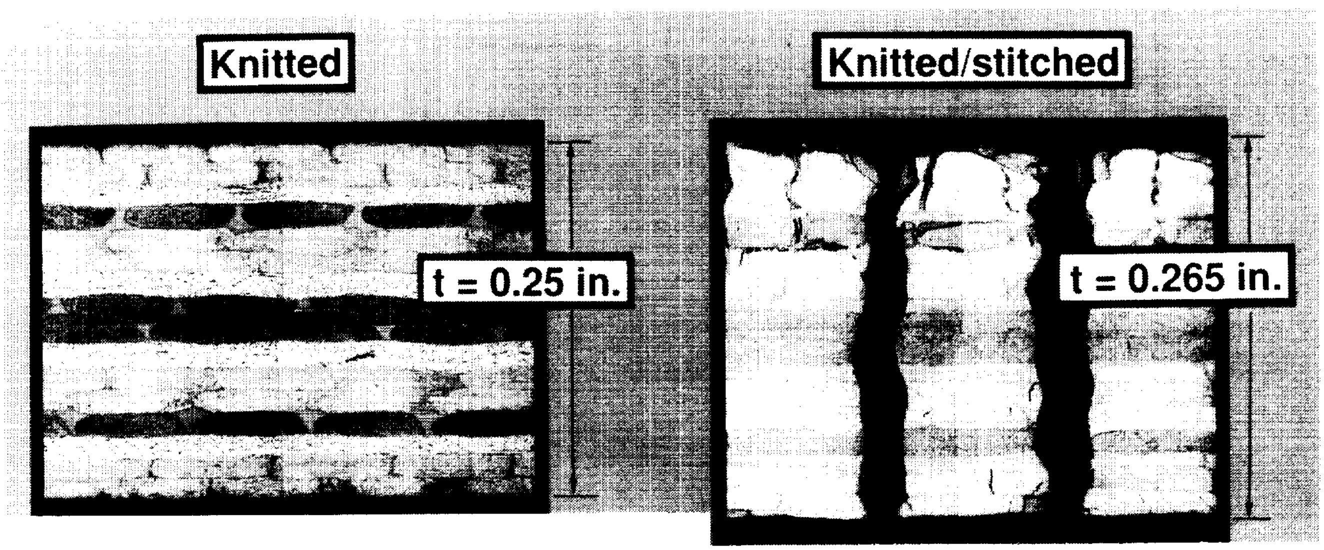

Figure 13

TEST SPECIMENS

The test specimens used in this investigation are shown in figure 14. All the test specimens had a nominal thickness of 0.250-inch and a nominal fiber volume fraction of 60 percent. The short block compression specimens were 1.50 inches wide by 1.75 inches long, and the compression-compression fatigue specimens were 1.5 inches wide by 4.0 inches long. The tension specimens were 1.0 inch wide by 10.0 inches long. The tension and compression specimens had 1/8-inch long (0/90) stacked strain gages bonded back-to-back at mid-length of the specimens. The compression-after-impact specimens were 5.0 inches wide by 10.0 inches long and had 1/4-inch long strain gages bonded back-to-back as shown in the figure. The compression after impact specimens were impacted at approximately 30 ft-lb of energy with 0.500-inch diameter aluminum balls that were fired from an air gun. The target impact energy was 1500 in-lb per inch of laminate thickness. However, due to velocity limitations of the air gun, some of the thicker laminates were subjected to energies slightly lower than the desired level of 1500 in-lb per inch of laminate thickness.

Open hole tension and compression specimens were both 10.0 inches long and had 1/4-inch holes drilled through their centers. Tension specimens were 1.5 inches wide and compression specimens were 3.0 inches wide. Open hole specimens had 1/4-inch long strain gages bonded back-to-back as shown in the figure.

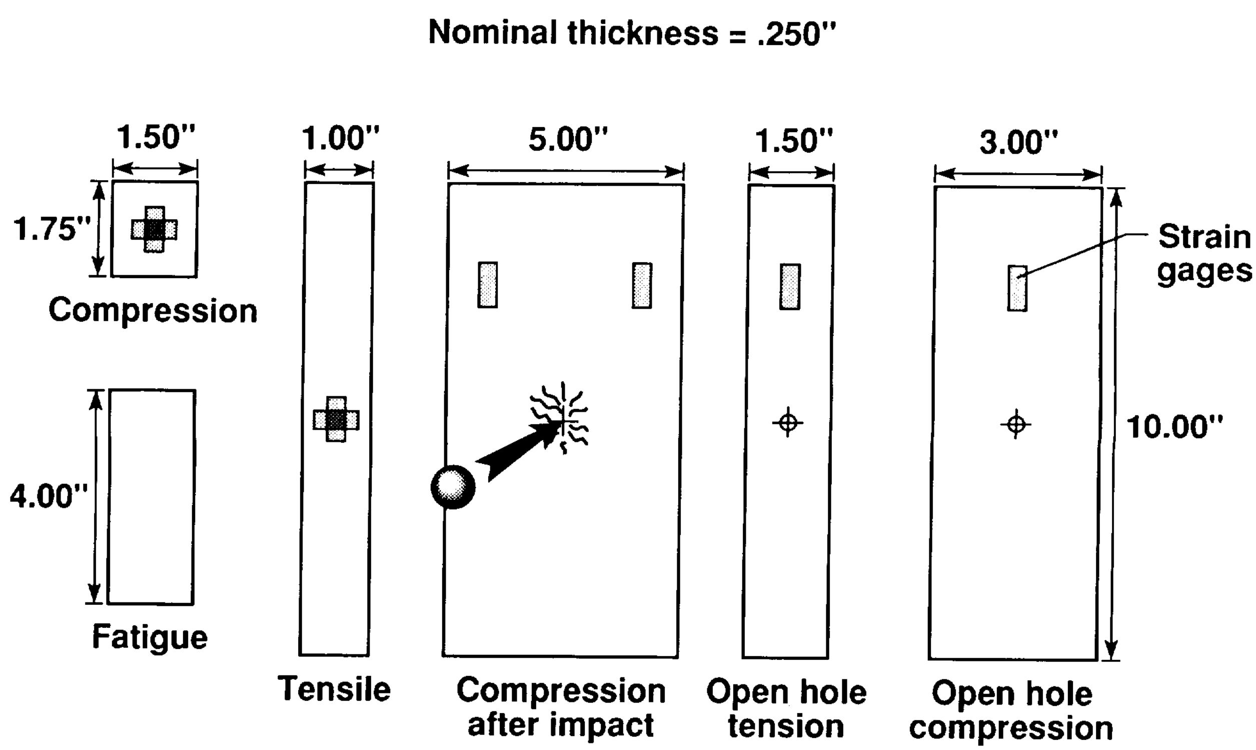

Figure 14

Sketches of the test fixtures used in this investigation are shown in figure 15. Tension and compression tests were performed to measure elastic properties and strength. Compression after impact tests were performed to determine the effect of low-velocity impact on the compression strength of the knitted fabrics. Open hole tension and open hole compression tests were performed to determine the effect of stress concentrations on residual strength. Constant amplitude compression-compression fatigue ($R = 10$) tests were conducted to assess the effect of cyclic loading on residual compression strength.

The compression specimens were tested in a short block compression fixture. This fixture was used to apply uniform end-loading and to apply lateral clamping forces to the specimen ends to prevent end-brooming type failures. The specimens were tested in a 120-Kip hydraulic test machine at a load rate of 10 Kips/min until failure. Selected compression specimens were moisture conditioned and tested at 180°F. Moisture absorption was achieved by immersion of the specimens in water for 45 days at 160°F. The compression after impact and open hole compression specimens were tested in a fixture that clamps the ends and provides knife-edge supports on the sides to prevent overall panel instability. The compression after impact specimens were loaded at 20 Kips/min and the open hole compression specimens were loaded at 15 Kips/min. The tension and open hole tension specimens were tested in a 50-Kip servo-hydraulic test machine. End tabs were not used but lexan and a grit-coated wire screen were used to prevent slippage and specimen damage due to hydraulic actuated grip pressure. The tension specimens were loaded at a displacement rate of 0.05 in/min until failure.

The fatigue tests were conducted in a closed-loop servo-hydraulic test machine at a frequency of 10 Hz. The maximum number of cycles applied to the specimens was approximately 3 million cycles. The fatigue test fixture has four alignment rods that slide on linear bearings. The gripping surfaces were serrated to prevent slippage and to transmit load. In addition, end stops were used to apply end loads and to prevent slippage of the specimens.

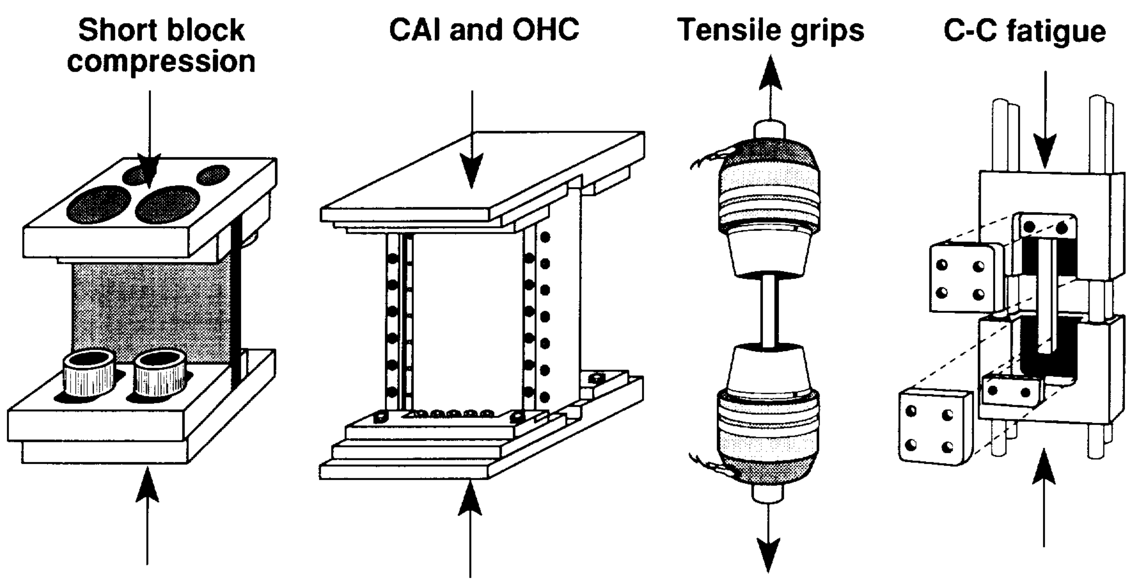

Figure 15

TENSILE STRENGTH OF HEXCEL HI-TECH FABRIC

Average tensile strengths for the Hexcel Hi-Tech knitted and knitted-stitched fabrics are shown in figure 16. Test results are shown for laminates fabricated with Hercules 3501-6 resin and Dow Tactix 138/H41 resin. The fabric results are compared with those for AS4/3501-6 prepreg tape. The prepreg laminates were fabricated with a $(+45_3,\ 0_3,\ -45_3,\ 90_3)_{2s}$ 48-ply layup which approximates the ply thicknesses for the 16-ply fabric layup. The test results indicate that the knitted-stitched laminates are stronger than the knitted laminates. These results are in contrast to results for Xerkon knitted-stitched laminates reported in reference 1, where it was found that stitching degrades the laminate tensile strength. The strength of the knitted laminates is approximately 22 percent lower than the strength of prepreg tape. The strength of the knitted-stitched laminates is only about 10 percent lower than the strength of the prepreg tape. Most of the tensile failures were in the test section; however, a few specimens failed at the edge of the grips. All specimens were tested without tabs in hydraulic pressure grips. It is possible that fiberglass tabs would improve load transfer and increase strength for all the laminates.

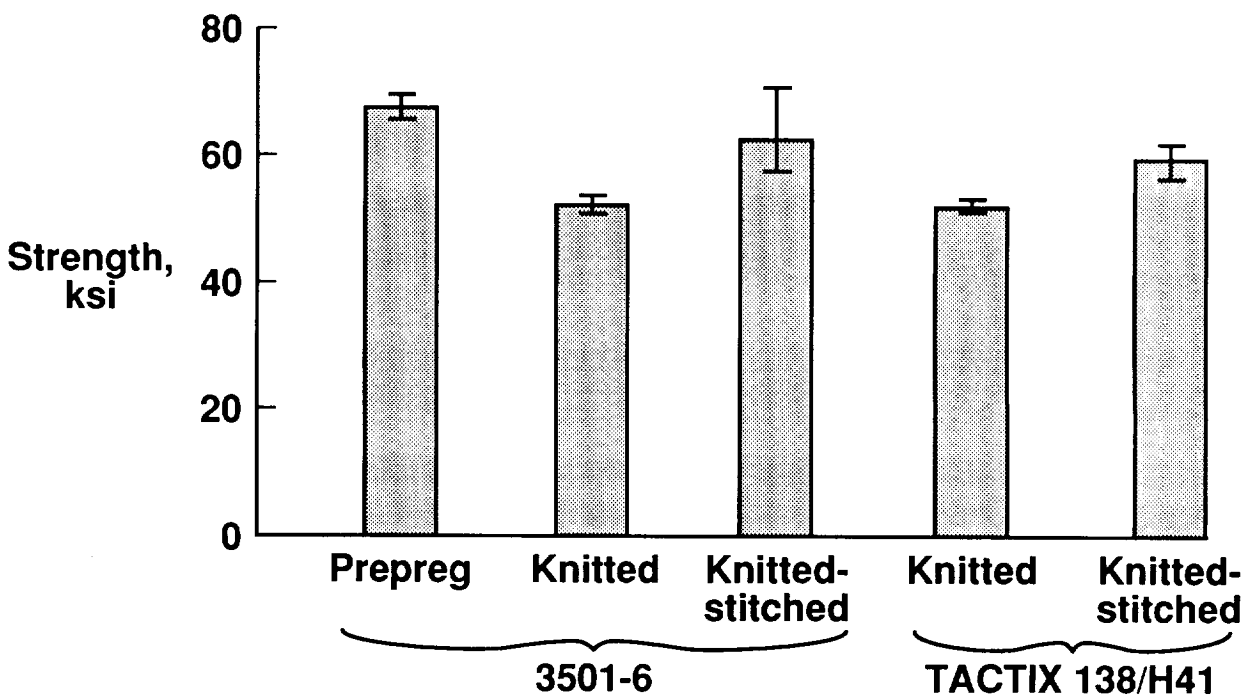

Figure 16

TENSILE STRENGTH OF MILLIKEN KNITTED FABRIC

Average tensile strengths for the Milliken knitted fabrics that were fabricated with 3501-6 resin and BP E905L resin are shown in figure 17. The strength of the 3501-6 knitted Milliken fabric is similar to the strength of the Hexcel Hi-Tech knitted fabric discussed in figure 16. The laminates with the E905L resin were about 17 percent stronger than the 3501-6 laminates. The Milliken prepreg laminate consisted of 48 plies of AS4/3501-6 prepreg tape which were stacked unsymmetrically to simulate the 16-ply Milliken knitted laminate discussed in figure 6. The average strength of the Milliken knitted laminates is approximately 26 percent lower than the strength of the prepreg tape. Due to a limited supply of Milliken fabric, knitted-stitched tensile specimens were not fabricated.

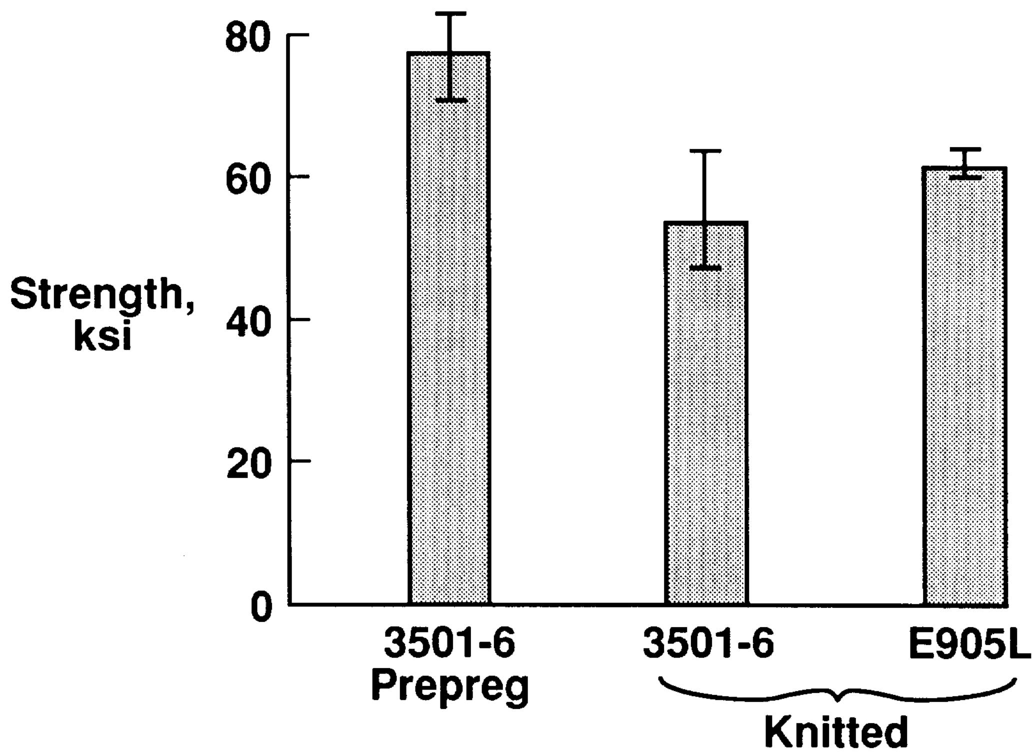

Figure 17

COMPRESSION STRENGTH OF HEXCEL HI-TECH FABRIC

Average compression strengths for the Hexcel Hi-Tech knitted and knitted-stitched fabrics are shown in figure 18. The average strength of the knitted and knitted-stitched fabrics is approximately 32 percent lower than the strength of the prepreg tape laminates. The failure mode for the tape and knitted laminates consisted of extensive ply delaminations, whereas the failure mode of the knitted-stitched laminates was primarily a transverse shear mode. Although the failure mode was significantly different between the knitted and knitted-stitched laminates, the stitching did not improve the strength. In fact, the strength of the knitted-stitched laminates with Tactix 138/H41 resin was lower than the strength of the knitted laminates. Since the modulus of the Tactix 138/H41 resin is lower than the modulus of the 3501-6 resin, it is expected that the compression strength of the laminates with Tactix 138/H41 resin would be lower.

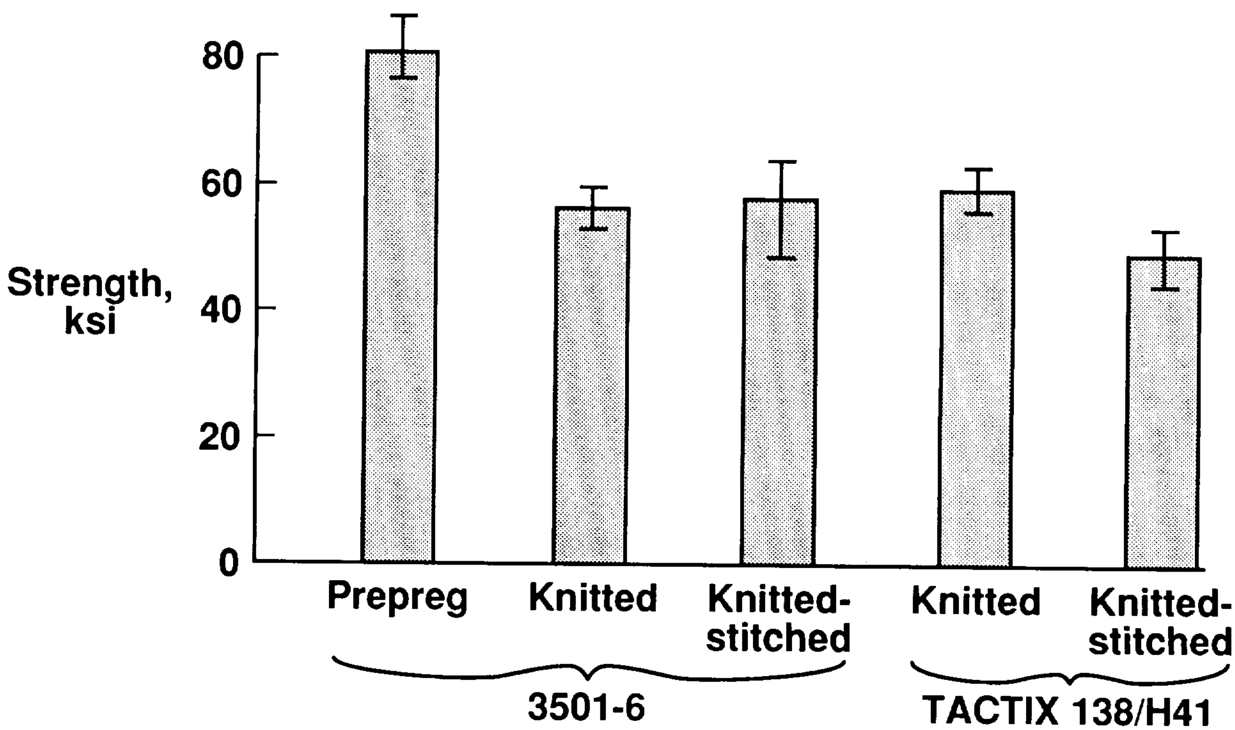

Figure 18

COMPRESSION STRENGTH OF MILLIKEN FABRIC

Average compression strengths for the Milliken knitted and knitted-stitched fabrics are shown in figure 19. The knitted fabrics with 3501-6 and E905L resins had compression strengths that were only about 10 percent lower than the strength of the prepreg tape laminates. There was only one Kevlar 29 stitched laminate available for testing; due to processing problems, this laminate had considerable porosity and its compression strength was lower than it should have been. Additional Milliken laminates will be fabricated and tested to assess the performance of Kevlar 29 stitching and E905L resin. The Milliken knitted fabric had better compression strength than the Hexcel Hi-Tech knitted fabric.

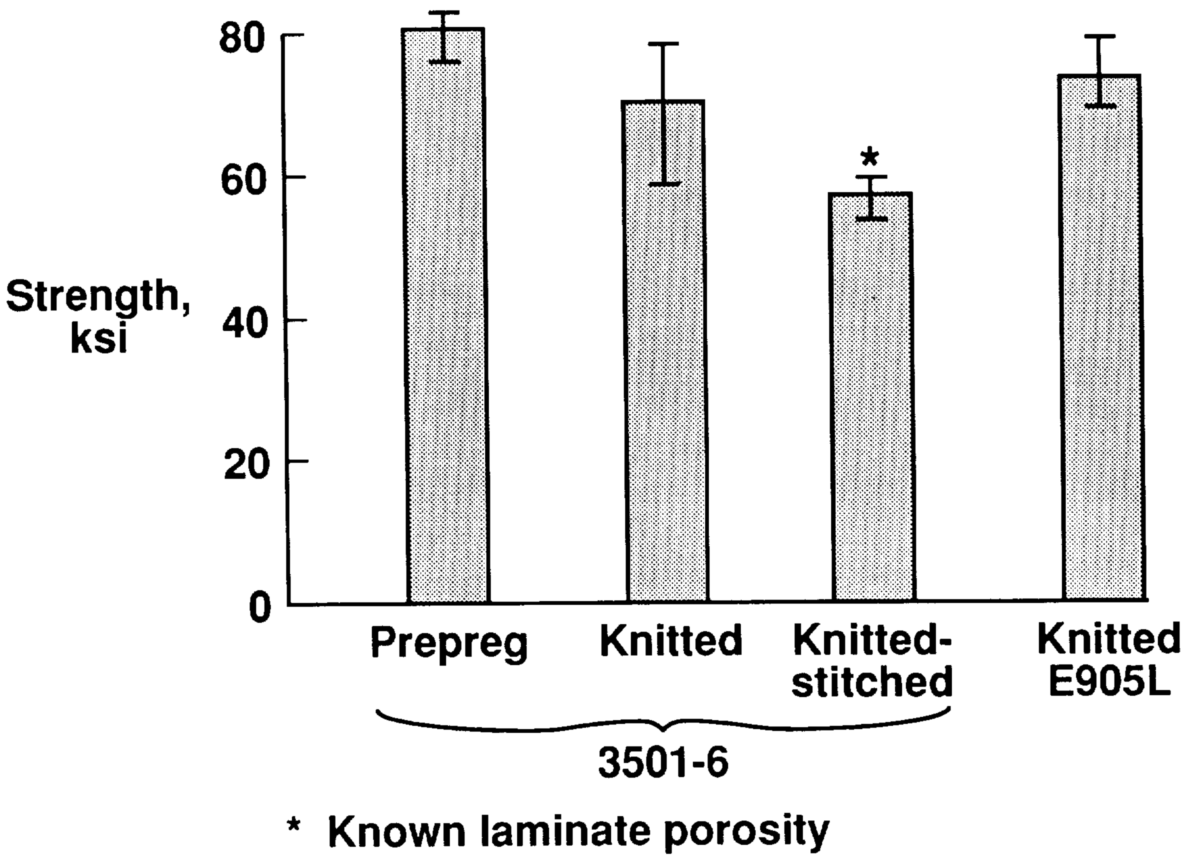

Figure 19

MODULUS OF HEXCEL HI-TECH FABRIC

Tensile and compression modulus data are presented in figure 20 for the Hexcel Hi-Tech fabric. The tensile modulus is slightly higher than the compression modulus for all the materials indicated in the figure. The moduli for the knitted and knitted-stitched fabrics are slightly lower than the corresponding moduli for the prepreg tape laminates. These results are expected since the through-the-thickness knitting and stitching yarns do not contribute to the in-plane material properties. In-plane fiber crimp could also lead to reduced in-plane moduli for the knitted and knitted-stitched composites.

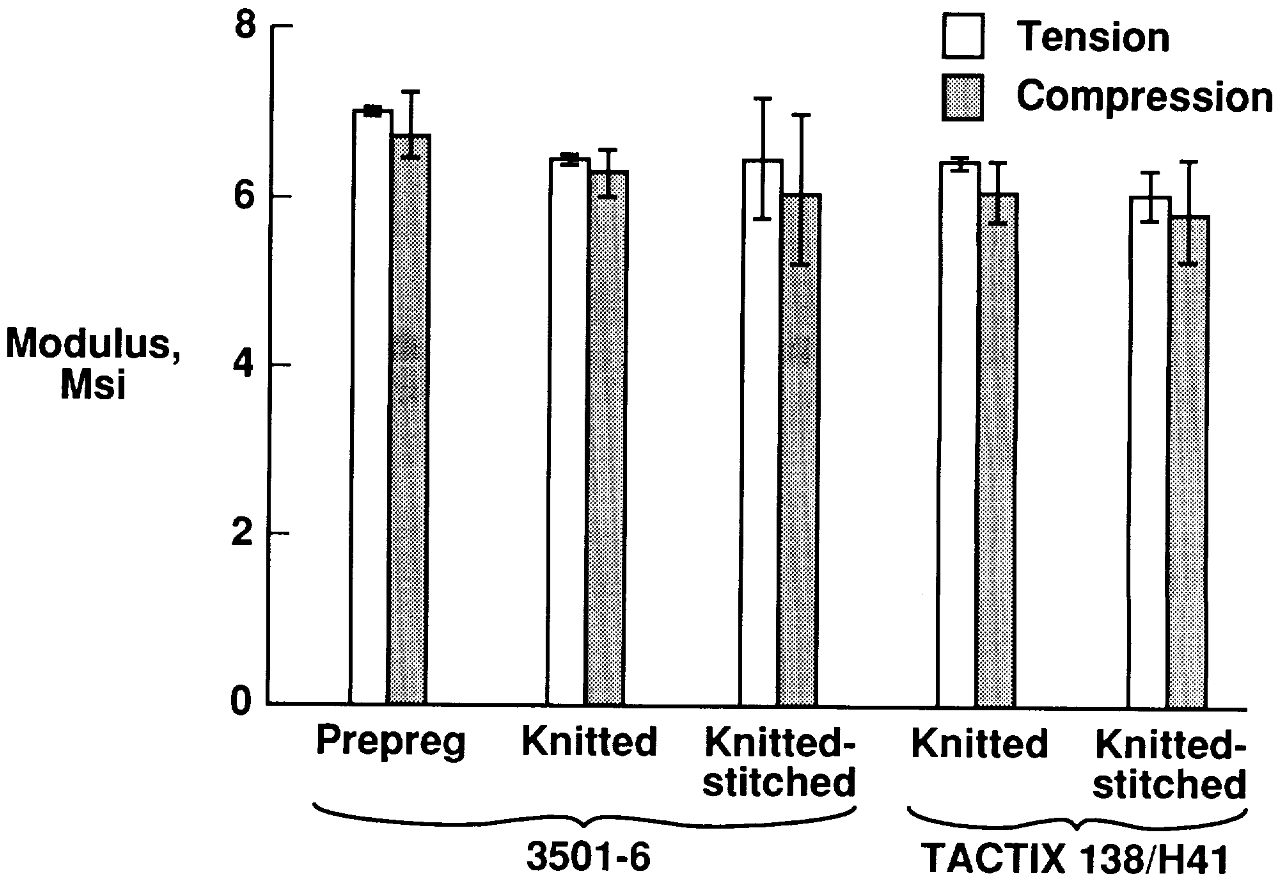

Figure 20

MODULUS OF MILLIKEN FABRIC

Tensile and compression modulus data are presented in figure 21 for the Milliken fabric. The tensile modulus is slightly higher than the compression modulus for all the materials indicated in the figure. The moduli for the 3501-6 knitted and knitted-stitched fabrics are slightly lower than the corresponding moduli for the prepreg tape laminates. The moduli for the E905L knitted fabric are equivalent to the prepreg tape moduli.

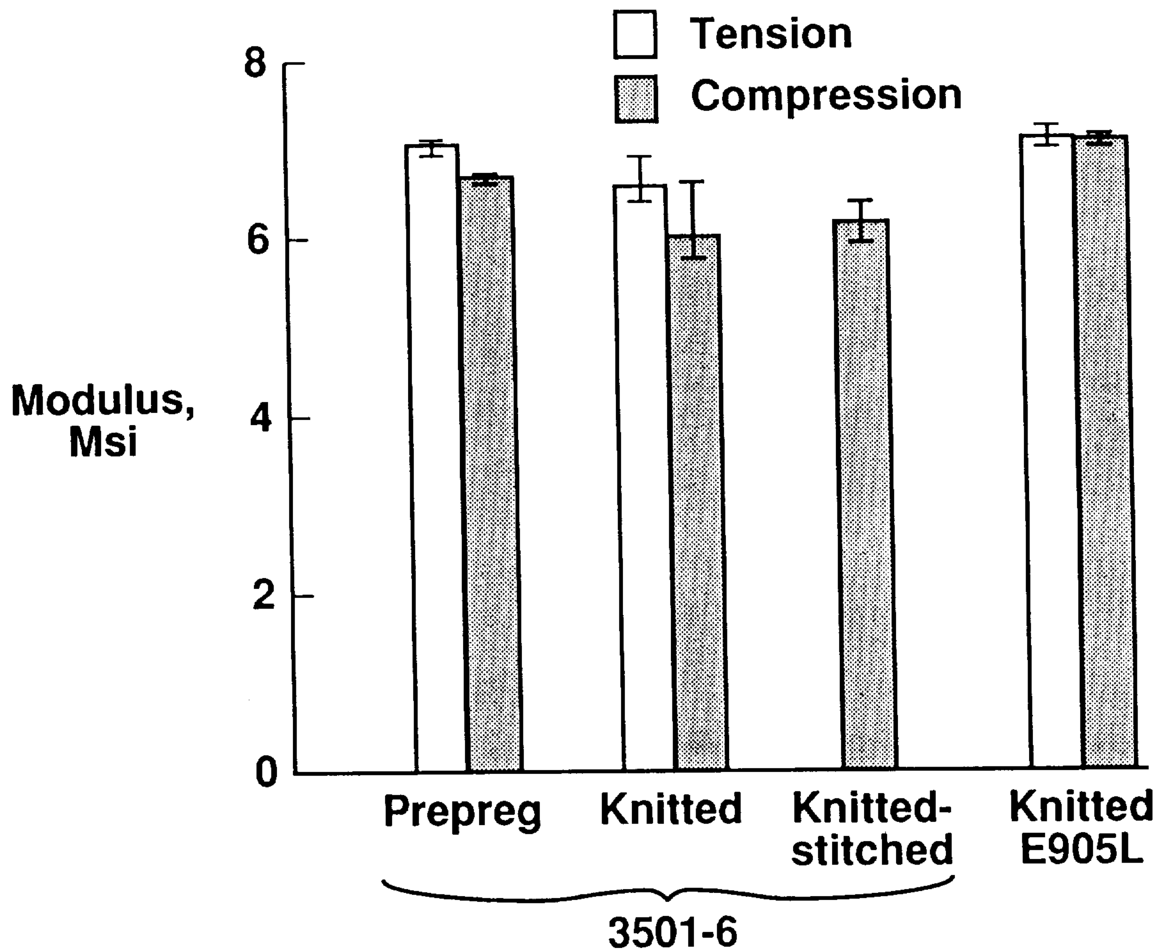

Figure 21

EFFECT OF MOISTURE AND TEMPERATURE ON COMPRESSION STRENGTH OF HEXCEL HI-TECH KNITTED-STITCHED FABRIC

The effect of moisture and temperature on the compression strength of the Hexcel Hi-Tech knitted-stitched fabric is shown in figure 22 for the 3501-6 and Tactix 138/H41 resin systems. Ten coupons were taken from panels made with each resin. Five of each were tested at ambient conditions, and another five of each were conditioned and tested at elevated temperature. The compression coupons were soaked in a water bath at 160°F for 45 days to moisture condition the coupons. The 3501-6 coupons absorbed 1.1 percent moisture whereas the Tactix 138/H41 coupons absorbed only 0.6 percent moisture. After moisture conditioning, the coupons were tested at 180°F in an environmental chamber. The test results indicate that the compression strength of the 3501-6 material was reduced by 28 percent compared to the ambient compression strength. The compression strength of the Tactix 138/H41 material was reduced by 24 percent compared to ambient compression strength. As expected, the lower moisture absorption for the Tactix 138/H41 resin system resulted in a somewhat lower percentage reduction in compression strength. As shown in figure 22, the ambient compression strength of the Tactix 138/H41 resin system was about 20 percent lower than the ambient compression strength of the 3501-6 resin system.

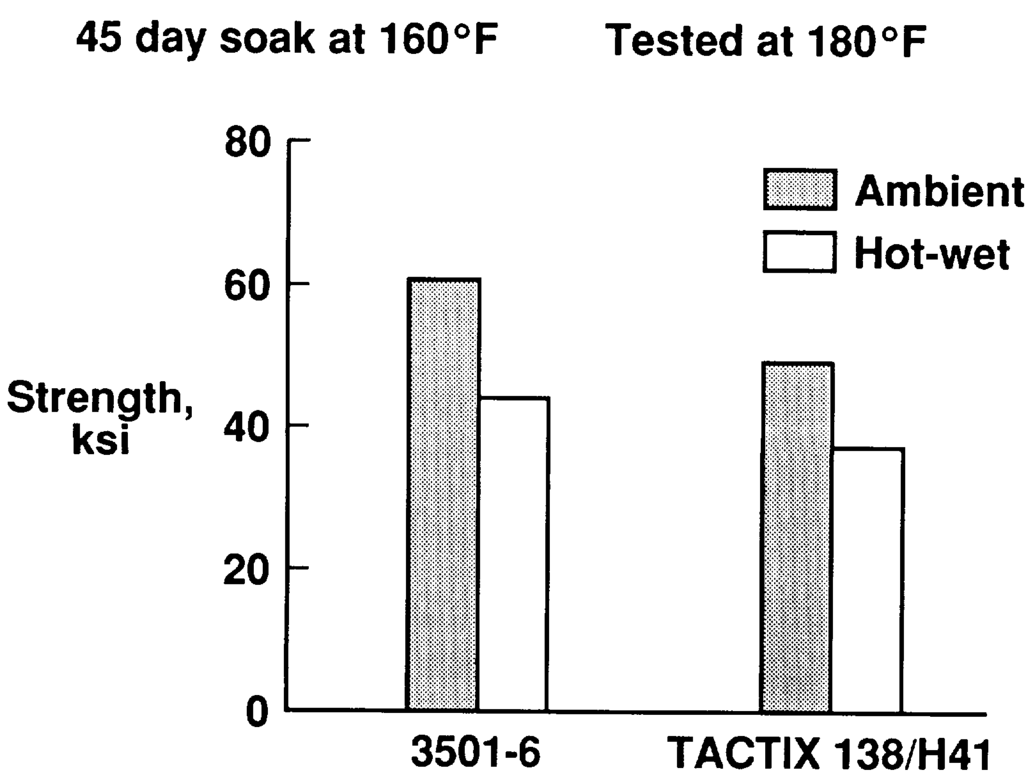

Figure 22

EFFECT OF IMPACT ON COMPRESSION STRENGTH
OF HEXCEL HI-TECH FABRIC

The effect of impact on the compression strength of the Hexcel Hi-Tech fabric is shown in figure 23. The knitted and knitted-stitched fabrics are compared to prepreg tape laminates with similar ply orientations. A 30 ft-lb impact reduced the compression strength of the 3501-6 prepreg laminate from 80 ksi to less than 20 ksi. Although the baseline strengths of the 3501-6 and Tactix 138/H41 knitted laminates were 20 ksi lower than the strength of the prepreg tape laminates, compression after impact strengths were slightly higher. Stitching the knitted fabrics resulted in over 100 percent increase in compression after impact strength compared to the prepreg tape laminates. Although the baseline compression strength of the Tactix 138/H41 knitted-stitched laminates was somewhat lower than the strength of the 3501-6 knitted-stitched laminate, the strength after impact was similar for the two resin systems.

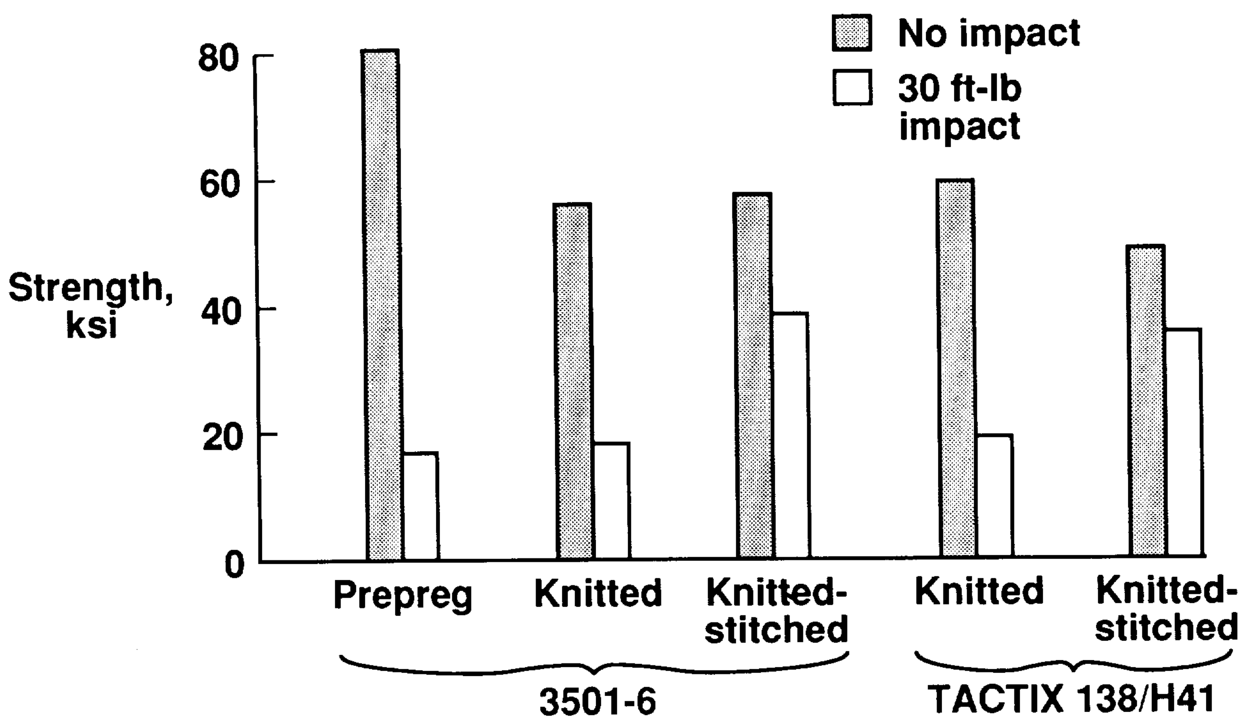

Figure 23

EFFECT OF IMPACT ON COMPRESSION STRENGTH OF MILLIKEN FABRIC

The effect of impact on the compression strength of Milliken fabric is shown in figure 24. As for the Hexcel prepreg tape laminates, a 30 ft-lb impact reduced the strength of the Milliken prepreg tape laminates from 80 ksi to less than 20 ksi. The knitted fabrics with the 3501-6 and E905L resin systems had a compression after impact strength of about 25 ksi. Only one Kevlar 29 stitched panel was fabricated and it had significant surface porosity and internal porosity. Even with the porosity, the knitted-stitched laminate had a compression after impact strength of almost 40 ksi. This result indicates the significant role that through-the-thickness reinforcement plays in improving the damage tolerance of composite materials.

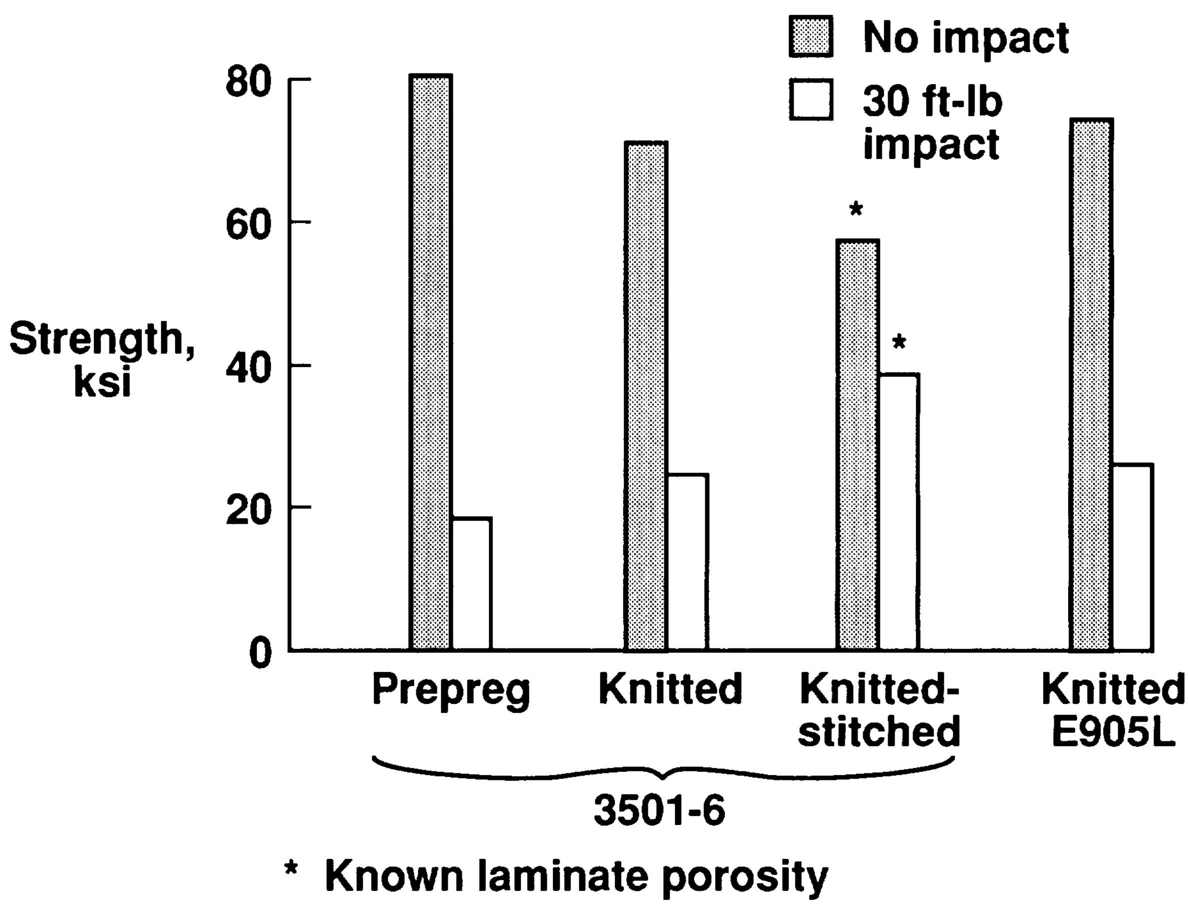

Figure 24

EFFECT OF IMPACT DAMAGE AREA ON COMPRESSION STRENGTH OF HEXCEL HI-TECH AND MILLIKEN FABRICS

The effect of damage area on the compression strength of the Hexcel Hi-Tech and Milliken fabrics is shown in figure 25. The damage areas plotted are a result of a 30 ft-lb impact and were detected by ultransonics and were calculated by computer image analysis. The prepreg tape laminates and the knitted Hexcel Hi-Tech laminates had the most damage and the lowest strength. The least amount of damage, approximately 5 in^2, was sustained by the Hexcel Hi-Tech and Milliken knitted-stitched fabrics. The Milliken knitted-stitched fabric achieved the highest strength, about 40 ksi. The somewhat higher strength and lower damage area of knitted, unstitched Milliken material compared to the knitted, unstitched Hexcel material may be due to three parameters: higher weight knitting yarn, tighter knit spacing and more knitted plies per subgroup.

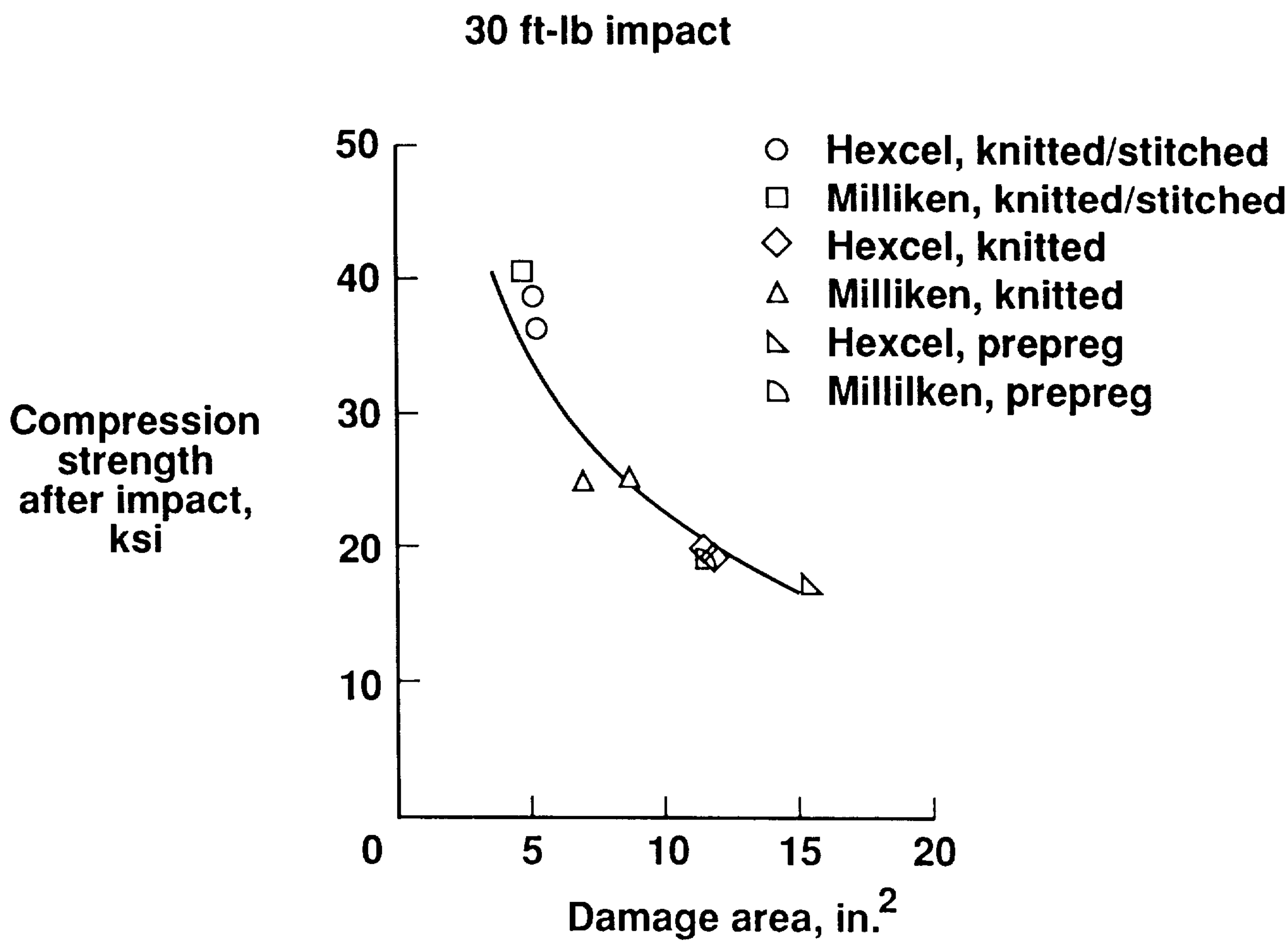

Figure 25

OPEN HOLE TENSILE STRENGTH OF HEXCEL HI-TECH FABRIC

The effect of a 1/4-inch diameter hole on the tensile strength of the Hexcel Hi-Tech fabric is shown in figure 26. The reduction in tensile strength due to the hole is less than would be expected based on loss in cross-sectional area. This result may indicate grip effects on the unnotched tensile strength. The open hole tensile strengths for the 3501-6 and Tactix 138/H41 resin systems are similar to the strengths reported in reference 4 for three AS-4/epoxy laminated tape composite material systems.

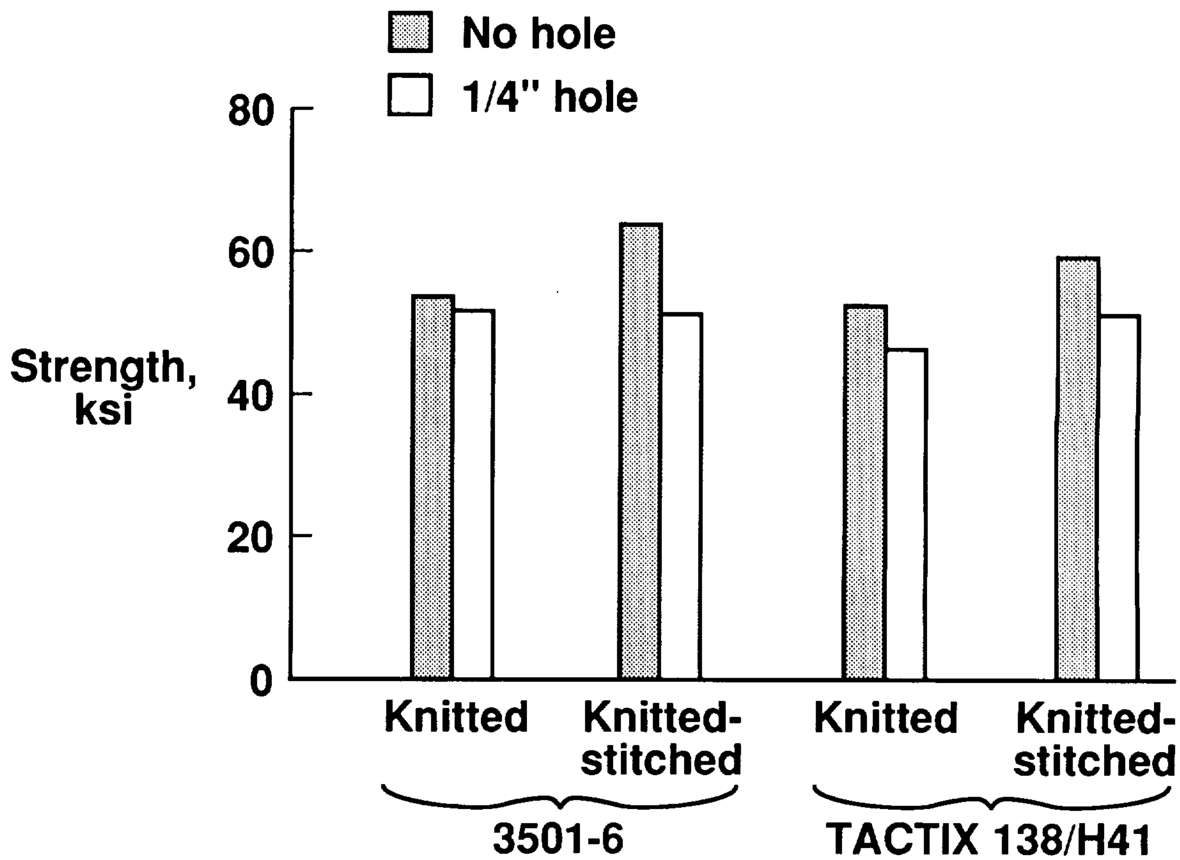

Figure 26

OPEN HOLE COMPRESSION STRENGTH OF HEXCEL HI-TECH AND MILLIKEN FABRICS

The effect of a 1/4-inch diameter hole on the compression strength of the Hexcel Hi-Tech and Milliken fabrics is shown in figure 27. Although the open hole compression specimens are twice as wide as the open hole tension specimens, the strength reduction in compression was significantly more. The open hole compression strengths for the fabrics indicated in figure 27 ranged from 40 to 50 ksi. These results are in agreement with laminated tape data presented in reference 4 for three AS-4/epoxy composite material systems. The Milliken fabric performed slightly better than the Hexcel Hi-Tech fabric.

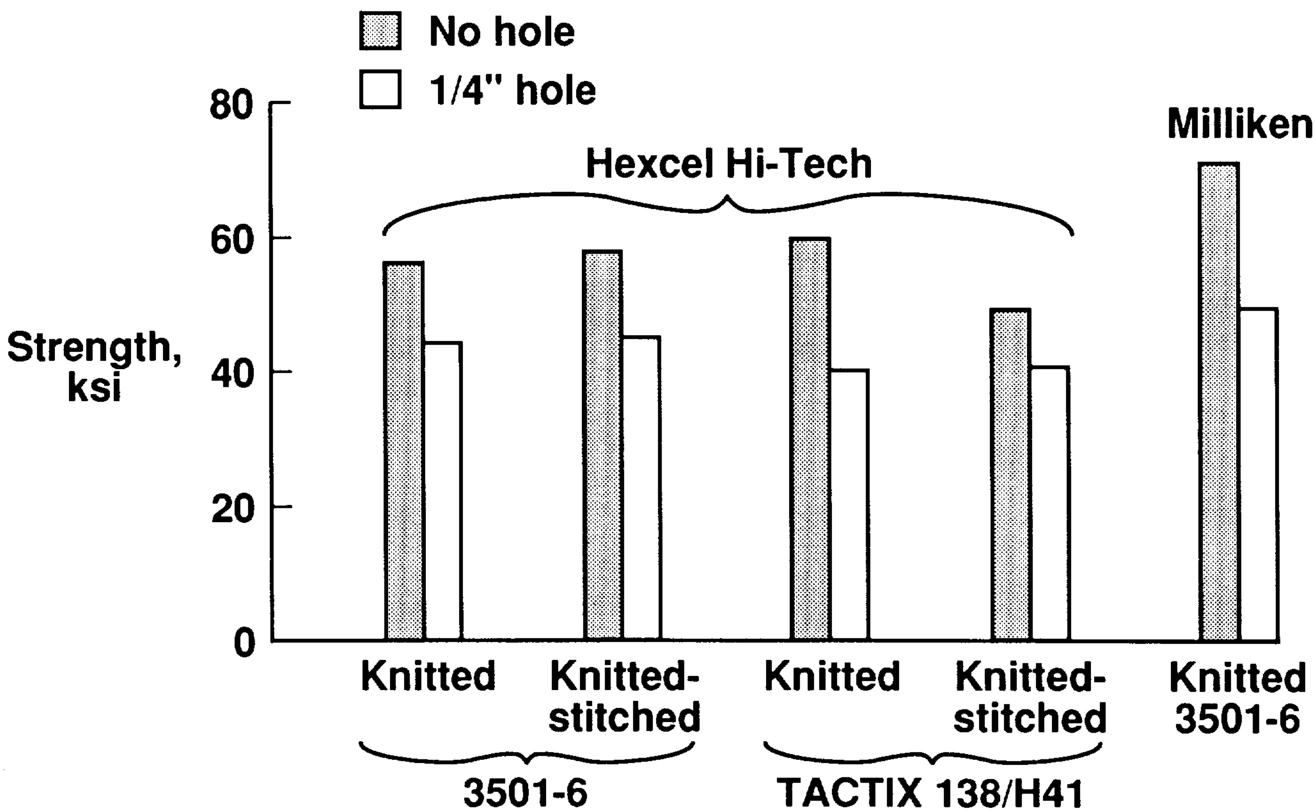

Figure 27

Constant amplitude compression-compression fatigue tests were conducted on the Hexcel Hi-Tech knitted-stitched fabric and the results are shown in figure 28. Hercules AS-4 fiber with both Hercules 3501-6 and Dow Tactix 138/H41 resins were used to fabricate laminates. The test specimens were 1.5 inches wide by 4.0 inches long with a nominal thickness of 0.25-inch. The fatigue tests were run at room temperature in a closed-loop servo-hydraulic test machine at a frequency of 10 Hz. All specimens were tested with an R-ratio (minimum load/maximum load) of 10.

The tests were conducted by subjecting the test specimens to selected stress levels and cycling the specimens until failure. The static compression strength (one cycle to failure) of the 3501-6 specimens was approximately 28-percent higher than the static strength of the Tactix 138/H41 specimens. After the initial knockdown in strength in the Tactix 138/H41 material, the two materials had similar S-N curves. Due to the initial strength knockdown, the 3501-6 specimens had longer fatigue lives for a given stress level. Observation of selected specimens during testing indicated that damage initiated earlier in the 3501-6 specimens; however, the damage did not grow as fast compared to the Tactix 138/H41 specimens. Tactix 138/H41 is a softer (lower modulus) resin, which may account for this behavior.

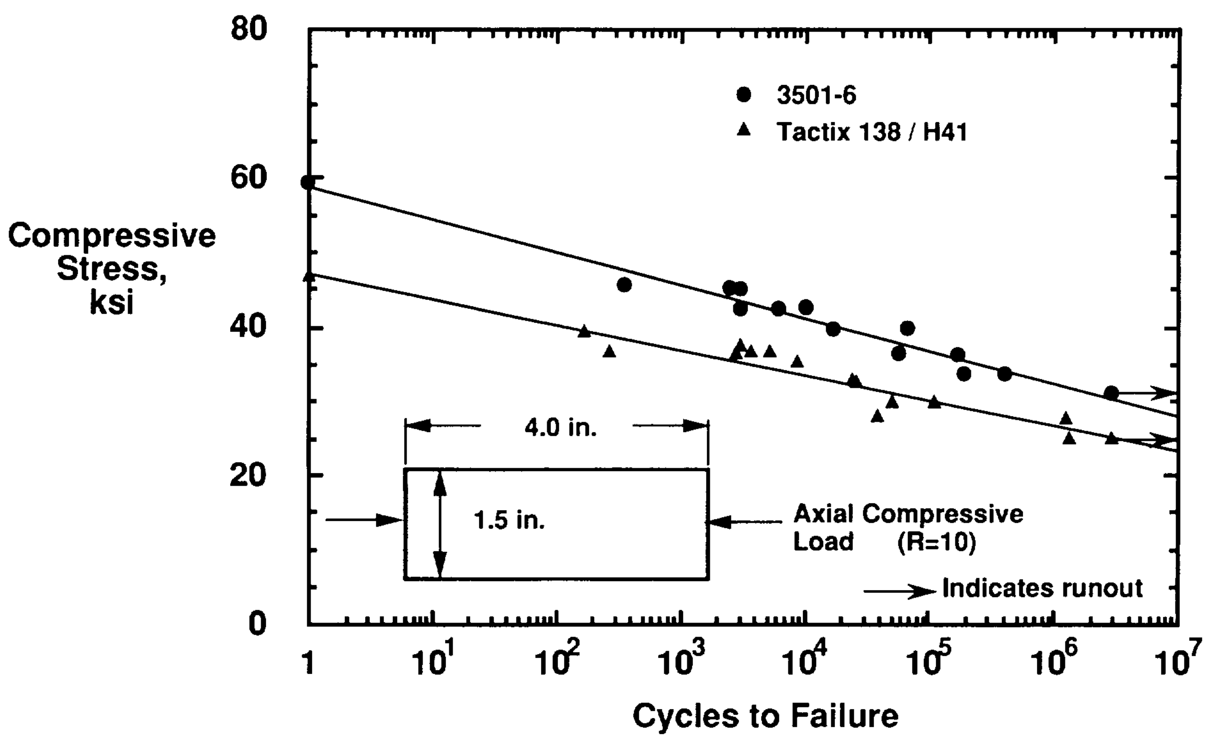

Figure 28

CONCLUDING REMARKS

Two relatively new multiaxial warp knitting processes were evaluated to establish their potential to produce aerospace quality fabrics for composite structural applications. Quasi-isotropic knitted fabrics were procured from Hexcel Hi-Tech and Milliken and composite laminates were fabricated with three different resin systems. Some of the laminates were stitched prior to resin impregnation to assess improvements in damage tolerance that may be achievable. Compaction and permeability studies were conducted on the dry fabric preforms to aid in development of infiltration and cure cycles. Viscosity profiles and cure cycles for each resin were developed to insure high quality composite laminates. Low void content composite laminates were fabricated with vacuum infiltration and pressure resin transfer molding processes.

Prepreg laminated tape composites simulating the multiaxial knitted fabrics were fabricated for property comparisons. The knitted fabric composites had tension and compression strengths that were lower than the tape composite strengths by as much as 32 percent. The knitted-stitched composites exhibited compression after impact strengths that were over 100 percent better than the strength of prepreg tape laminates. Good open hole tension and compression strengths were exhibited by the Hexcel Hi-Tech fabric. In general, the Dow Tactix 138/H41 resin did not perform as well as the Hercules 3501-6 and BP E905L resins.

Only a small quantity of the Milliken fabric was available for evaluation. The preliminary results look promising and additional material will be fabricated for a more thorough investigation. The results of this research investigation indicate that the Hexcel Hi-Tech and Milliken multiaxial warp knit machines can produce high quality broadgoods suitable for many aerospace composite applications. New resin systems that have been formulated for resin transfer molding look promising and significant cost savings may be possible through the use of dry textile preforms and resin transfer molding.

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