

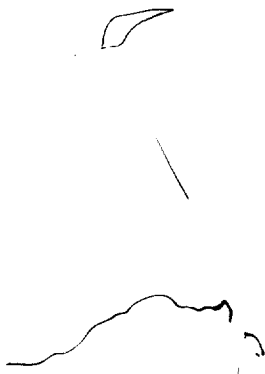
AN OVERVIEW OF THE NASA TEXTILE COMPOSITES PROGRAM

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INTRODUCTION

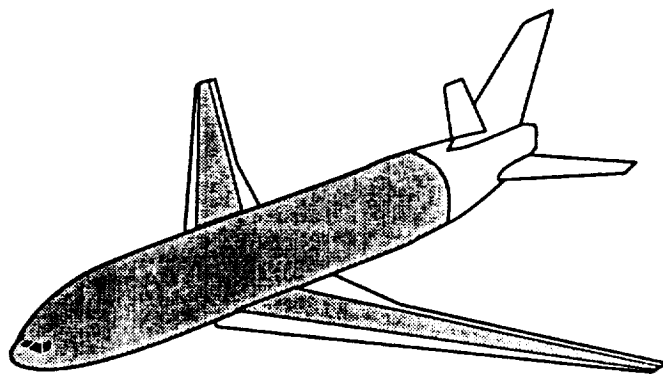
The NASA Langley Research Center is conducting and sponsoring research to explore the benefits of textile reinforced composites for civil transport aircraft primary structures. The objective of this program is to develop and demonstrate the potential of affordable textile reinforced composite materials to meet design properties and damage tolerance requirements of advanced aircraft structures. In addition to in-house research, the program includes major participation by the aircraft industry and aerospace textile companies. The major program elements include development of textile preforms, processing science, mechanics of materials, experimental characterization of materials, and development and evaluation of textile reinforced composite structural elements and subcomponents. The NASA Langley in-house research is focused on science-based understanding of resin transfer molding (RTM), development of powder-coated towpreg processes, analysis methodology, and development of a performance database on textile reinforced composites. The focus of the textile industry participation is on development of multidirectional, damage-tolerant preforms, and the aircraft industry participation is in the areas of innovative design concepts, cost-effective fabrication, and testing of textile reinforced composite structural elements and subcomponents.

Textile processes such as 3-D weaving, 2-D and 3-D braiding, and knitting/stitching are being compared with conventional laminated tape processes for improved damage tolerance. Through-the-thickness reinforcements offer significant damage tolerance improvements. However, these gains must be weighed against potential loss in in-plane properties such as strength and stiffness. Analytical trade studies are underway to establish design guidelines for the application of textile material forms to meet specific loading requirements. Fabrication and testing of large structural components are required to establish the full potential of textile reinforced composite materials. The goals of the NASA Langley-sponsored research program are to demonstrate technology readiness with subscale composite components by 1995 and to verify the performance of full-scale composite primary aircraft structural components by 1997. The status of textile reinforced composite structural elements under development by Boeing, Douglas, Lockheed, and Grumman are presented. Included are braided frames and woven/stitched wing and fuselage panels.



CURRENT STATE OF COMPOSITES TECHNOLOGY FOR TRANSPORTS

The goals of the NASA ACT program include extensive application of advanced composite materials to primary wing and fuselage structures, reduction of the structural weight by 30 to 50 percent, and development of cost-effective fabrication methods. In general, advanced composite materials have been limited to secondary structures. A 25-percent weight saving has been achieved, but the use of brittle materials dictated low-strain designs. In addition, development of automated fabrication processes has been slow. Some of the barriers to expanded application of composites in primary wing and fuselage structures are indicated in figure 1.



Goals

- Extensive application to wing and fuselage structures
- 30 to 50% weight reduction
- Cost effective fabrication

Status

- Limited to secondary structures
- 25% weight reduction achieved
- Brittle materials dictate low-strain designs
- High fabrication costs

Barriers

- Low damage tolerance of laminated constructions
- Expensive prepreg materials
- Labor intensive manufacturing
- Insufficient data base
- Inadequate analytical tools

Figure 1

TEXTILE REINFORCED COMPOSITES

The NASA Langley Research Center has assembled a multidisciplinary team to conduct research on textile reinforced composites. The current team includes NASA Langley in-house personnel, numerous universities, textile fabricators, and major aerospace contractors. The team will expand to meet program needs as required. Figure 2 indicates the scope of the research effort that is currently underway. Recent program emphasis has been on development of aircraft quality textile preforms, development of science-based processes, development of mechanics methodologies, and experimental characterization of textile reinforced composite materials. These technologies are maturing and future emphasis will shift to design, analysis, fabrication, inspection, and test of structural elements and subcomponents. Douglas, Lockheed, Boeing, and Grumman have provided a much needed focus on realistic airframe structures.

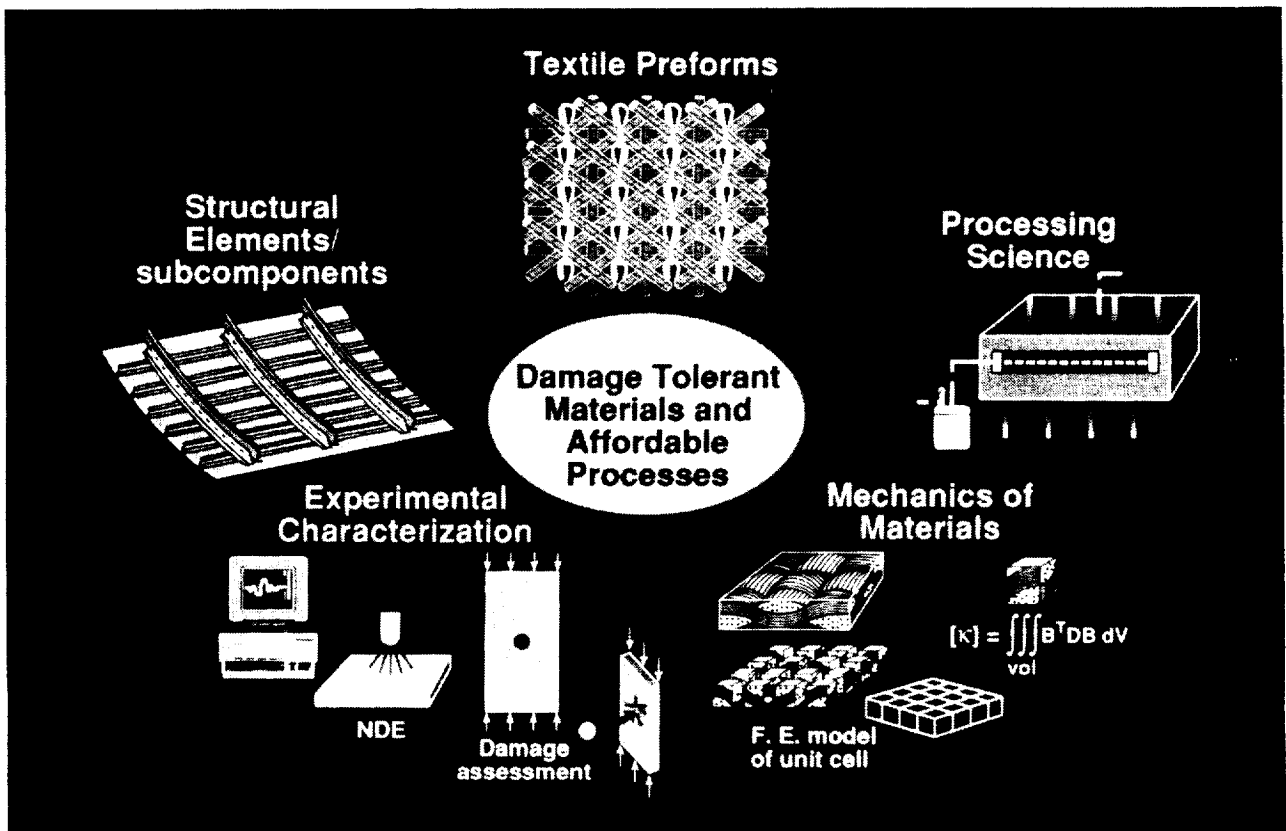


Figure 2

TEXTILE MATERIAL FORMS OF INTEREST

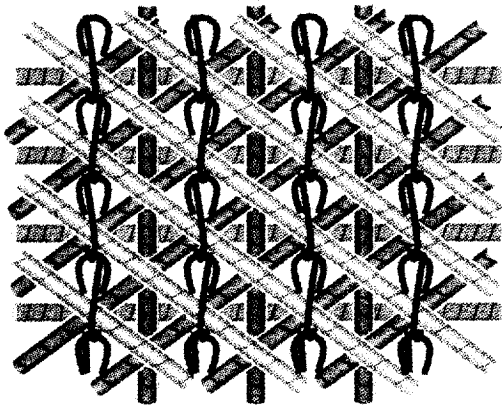
Textile material forms that have the most potential for primary aircraft structural applications are indicated in figure 3. The ultimate goal is to minimize the number of individual plies required to build-up part thickness. Integral weaving and braiding will result in near-net structural shapes that require only minimal machining and fastening. Multilayer-multiaxial knitted fabrics are being investigated as a cost-effective replacement for biaxial woven broadgoods. The knitted fabrics can be postformed to achieve selected structural shapes. If high concentrations of 0-degree reinforcements are required, low crimp uniweave fabric can be added to woven, knitted, or braided material forms. Through-the-thickness stitching has been used to provide improved out-of-plane strength, damage tolerance, and delamination resistance. It is expected that continued developments in automation of textile processes will result in significant cost savings in fabricating textile preforms for aircraft structures.

- **Low crimp uniweave fabric**
- **Integrally woven fabric shapes (2-D, 3-D)**
- **Multiaxial knitted fabric (0, 90, $\pm\theta$)**
- **Braided preforms (2-D, 3-D, interlock)**
- **Stitched combinations of woven, knitted and braided preforms**

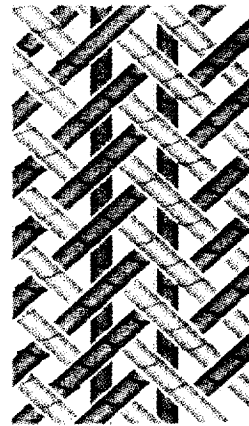
Figure 3

TEXTILE MATERIALS BEING EVALUATED

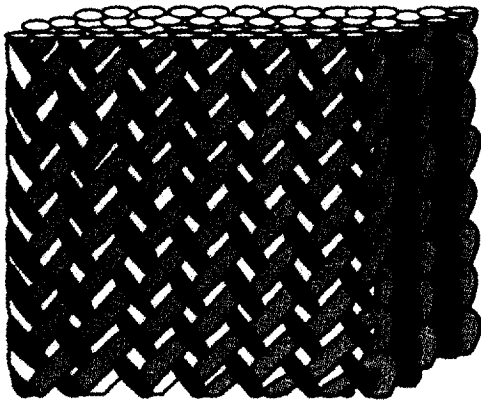
The textile materials that are currently being investigated in the NASA Langley program are shown in figure 4. Quasi-isotropic (+45, 0, -45, 90) multiaxial warp knit fabrics have been produced by Hexcel and Milliken. Tests have been completed to assess performance differences between 3, 6, and 12K tows. Kevlar and polyester knitting yarns and Kevlar and carbon stitching yarns are being investigated. Triaxial (0 ± 30) braids produced by Fiber Innovations have been evaluated. Both stitched and unstitched materials have been tested. Atlantic Research has produced 3-D braids for improved impact resistance and tests have been conducted. Test results have been compared to results for stitched triaxially braided materials. A new braiding process called layer-to-layer interlock has been developed by Albany International and tests are underway. Several different 3-D interlock weave configurations have been produced by Textile Technologies, Inc. All of these materials are being tested to assess mechanical properties and impact damage tolerance. Stitched uniweave fabric is being evaluated extensively by Douglas for damage tolerant wing structures.



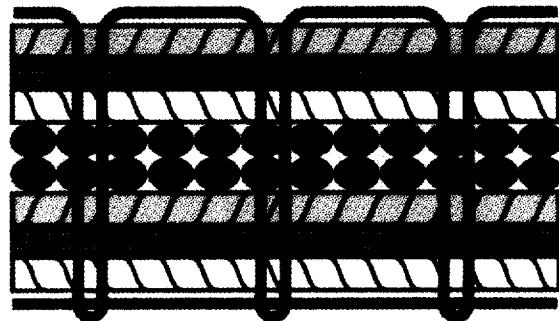
**Multiaxial warp knit
(stitched & unstitched)**



**2-D triaxial braid
(stitched & unstitched)**



3-D braid



Uniweave/stitched

Figure 4

NET-SHAPED TEXTILE PREFORMS

Some of the textile preforms that are being considered for structural applications are shown in figure 5. Weaving is well-suited for production of stiffened panels. However, automated weaving processes are currently limited to (0/90) fiber orientations in the skin and stiffening elements. Off-axis reinforcement, if required, must be bonded or stitched onto the surfaces of the (0/90) preform. Two-dimensional multilayer braiding is being used to produce complex curved shapes such as fuselage frames. The braiding process provides multidirectional fiber continuity throughout the preform structural shape. Both 2-D and 3-D braiding processes can produce structural shapes that are difficult or inefficient to achieve by other processes.

The knitted sine wave beam shown in figure 5 was produced by postforming knitted fabric to a specified shape. Epoxy powder tackifiers or stitching can be used to tack layers together. The integrally woven Y-spar shown in figure 5 can be produced in continuous lengths. As with the hat-stiffened panel, off-axis reinforcement must be added to the spar as a secondary operation.

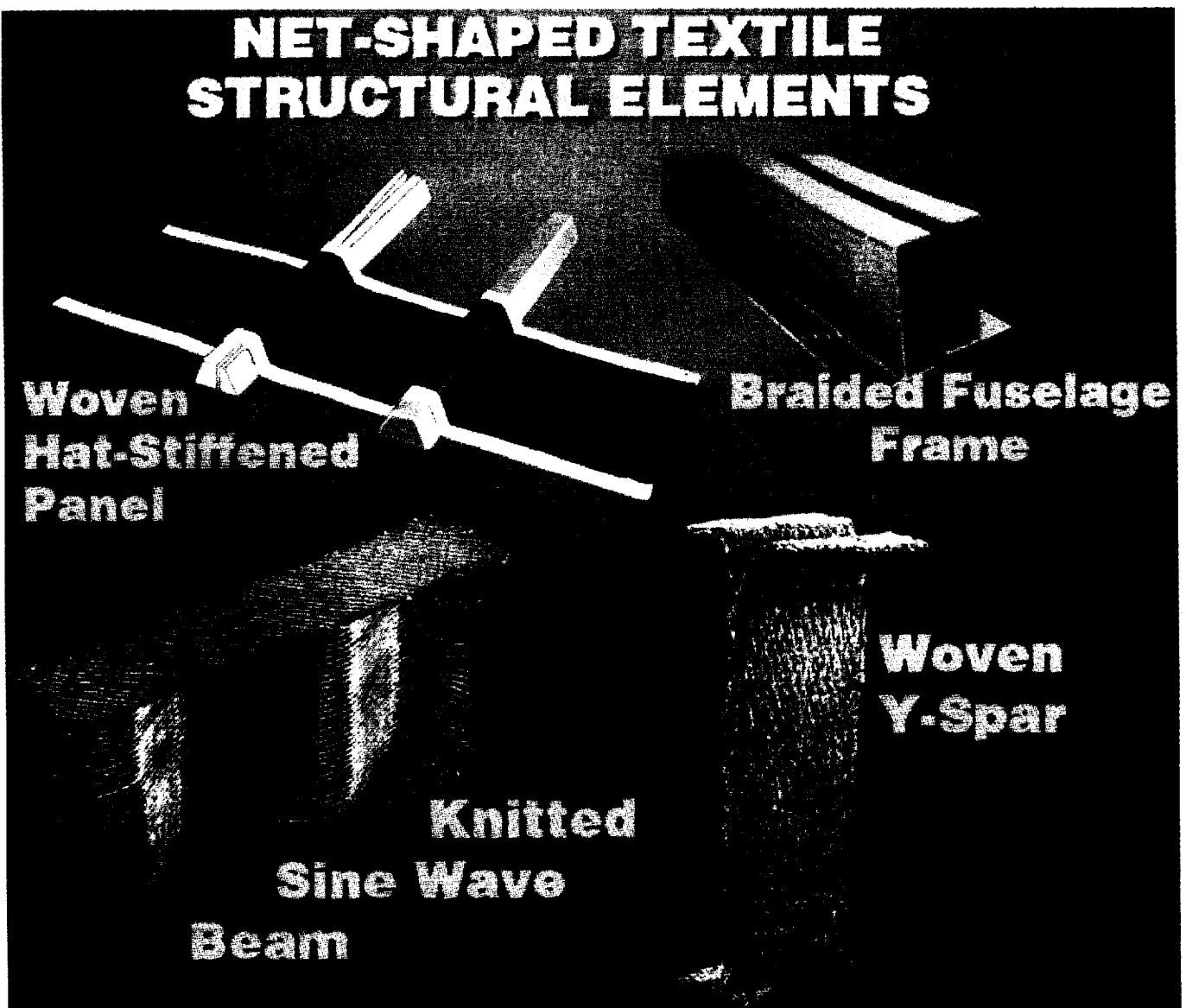


Figure 5

COST-EFFECTIVE PROCESSES AND FABRICATION METHODS

Cost-effective processes and fabrication methods must be developed to produce cost-competitive aircraft-quality composite structures from the preforms discussed previously. The objectives and program elements for this research are shown in figure 6. Two major areas of research focus are resin transfer molding (RTM) and powder-coated towpreg. RTM is one of the most promising processes to achieve cost-effective structures because it uses resins and fibers in their lowest cost form. RTM has been used for many years but previous applications did not have stringent performance requirements. New resins with enhanced flow properties, higher strength, and improved toughness are currently under development. Appropriate tooling concepts must be developed to make cost-effective use of RTM. Analytical models are being developed to understand the RTM process and to eliminate trial-and-error procedures that are commonly used.

Powdered resins are a potential alternative to RTM. Powder-coated tows, if properly prepared, can be used in textile processes such as weaving and braiding. Hence, pumping of resin into the preform, as with RTM, can be eliminated. The powder coating process is in its infancy and significant research is required before aircraft-quality composite structures can be produced. The research program elements shown in figure 6 are currently being pursued by NASA Langley, aerospace contractors, and universities.

- **Objectives**
 - **Develop innovative processes and tooling concepts for RTM**
 - **Optimize powder coating techniques, demonstrate weaving and braiding characteristics, and develop fabrication processes**
- **Program elements**
 - RTM**
 - **Improved RTM resins with high modulus, strength and toughness**
 - **Analytical processing science models for liquid, semi-solid and paste resins**
 - **Innovative compaction and tooling concepts for structural elements**
 - Powdered resins**
 - **Optimized powder coating techniques**
 - **Weaving and braiding trials**
 - **Fiber wet-out and preform consolidation studies**
 - **Tooling concepts for complex structural shapes**
 - **Technology demonstration through structural element fabrication**

Figure 6

PROCESSING SCIENCE OF TEXTILE REINFORCED COMPOSITES

Science-based processing studies are underway for textile reinforced composites. Analytical and experimental studies are being conducted to characterize preform and resin behavior for RTM. Major program elements are shown in figure 7. To model the RTM process, preform properties such as permeability and compaction, and resin viscosity as a function of temperature and time, must be known. Experimental studies are underway to determine preform permeability and compaction coefficients as a function of preform architecture. Resin infiltration studies are underway to predict how various resins flow through porous fiber preforms. Infiltration is affected by preform porosity, resin viscosity, flow direction, and applied pressure. Once the preforms are infiltrated, a cure kinetics analysis is performed to predict the degree of cure. A finite element analysis that utilizes preform and resin characteristic data has been employed to predict initial resin mass required, resin front position and time required for preform infiltration, resin viscosity and degree of cure, and final part thickness and fiber volume fraction.

Dielectric sensors are being used to track resin behavior as a function of time and to verify the RTM simulation model discussed above. The sensors can monitor infiltration position, resin viscosity, and degree of resin cure. The in-situ sensors can be used for real-time feedback control so that processing parameters can be modified if required. Flow visualization studies are being conducted to verify flow front position and to substantiate sensor output.

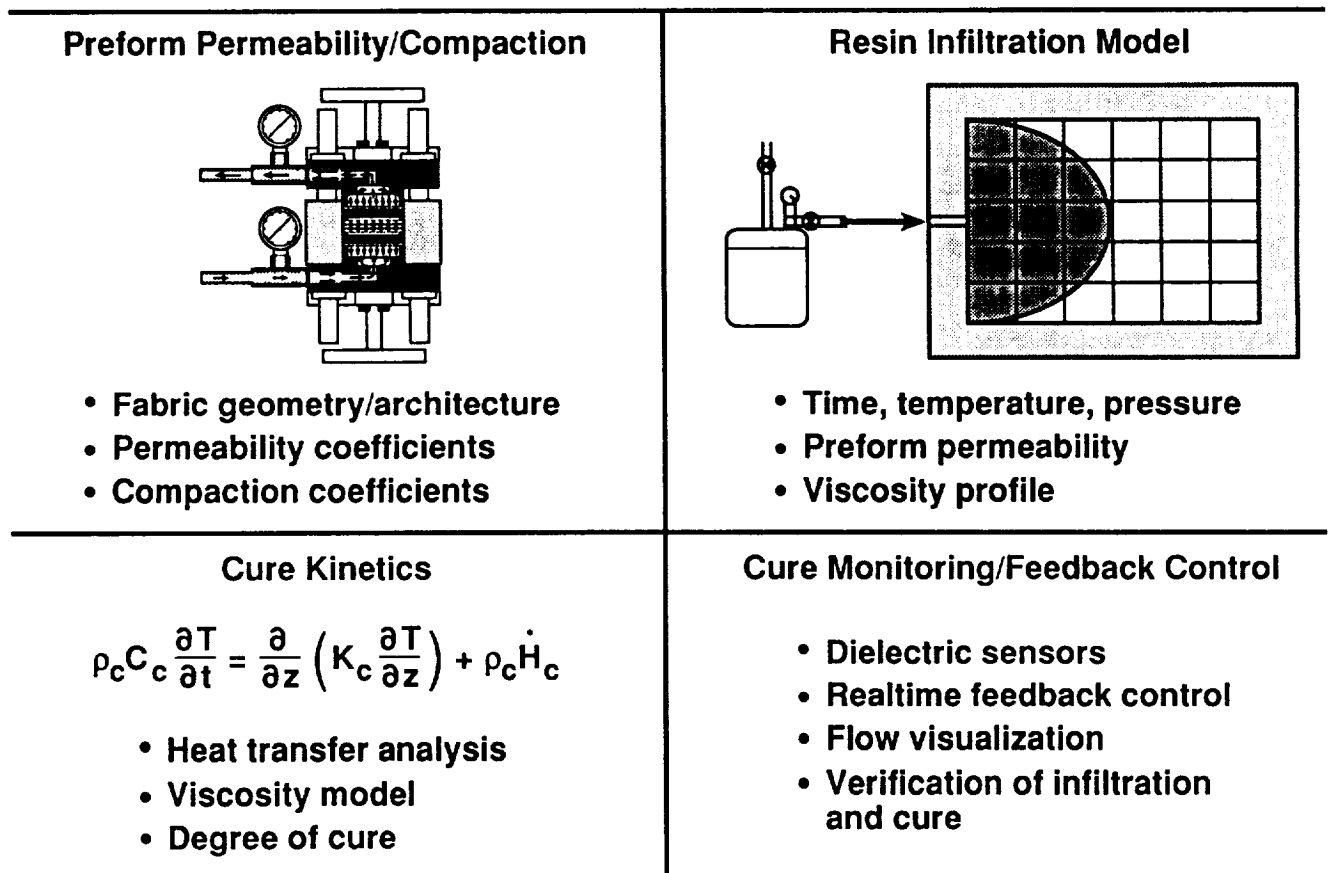


Figure 7

COMPACTION AND PERMEABILITY CHARACTERISTICS OF HEXCEL KNITTED FABRIC

An important part of resin transfer molding textile material forms is understanding the compaction and permeability characteristics of the material. Compaction and permeability coefficients can be used to predict fiber volume fraction and ease of resin infiltration. As shown in figure 8, fiber volume fraction and fabric thickness are nonlinear functions of compaction pressure. The Hexcel knitted fabric had a nominal uncompacted fiber volume fraction of approximately 37 percent and a thickness of approximately 0.39-inch. To achieve a fiber volume fraction of 60 percent and a final thickness of 0.250-inch, a compaction pressure of approximately 35 psig is required.

Also shown in figure 8 is the effect of fiber volume fraction on permeability. Permeability is a function of fabric architecture, compaction, porosity, and fluid flow direction. Permeability along a fiber bundle can be an order of magnitude greater than transverse to the fiber bundle. Permeability for the Hexcel knitted fabric is approximately $5 \times 10^{-10} \text{ in}^2$ for a fiber volume fraction of 60 percent. At a fiber volume fraction of 50 percent, the fabric would be much easier to infiltrate at a permeability of $14 \times 10^{-10} \text{ in}^2$.

(+45/0/-45/90)_{2s}

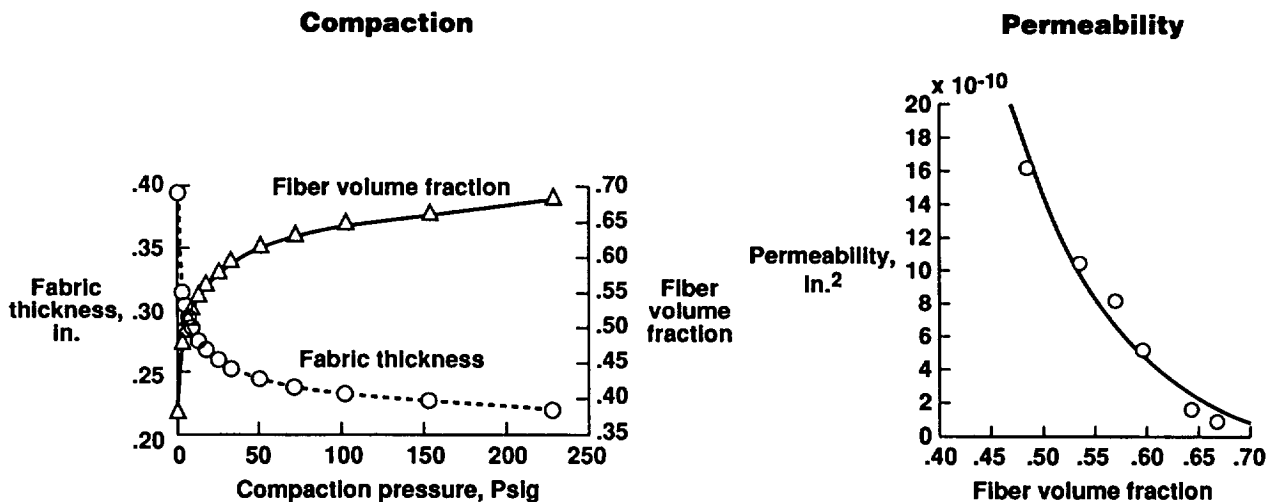


Figure 8

FLOW VISUALIZATION APPARATUS

Flow visualization experiments were conducted to vary analytical predictions of flow front position as a function of time. The experimental apparatus is shown in figure 9. Major components in the experimental set-up included an injection mold with a poly (methyl methacrylate) top plate, a video camera and high resolution tape recorder, and an air pressurized resin pot. In addition, a total of nine Frequency Dependent Electromagnetic Sensors (FDEMS) were mounted in the aluminum bottom plate of the mold. The output leads from the sensors were connected to a multiplexer which was used to analyze the signals from the sensors. Resin can be injected into the mold through a center injection port or side ports. Once the resin comes in contact with a particular sensor, a definitive change in the sensor output is recorded and the time required for sensor wet-out is compared with analytical predictions.

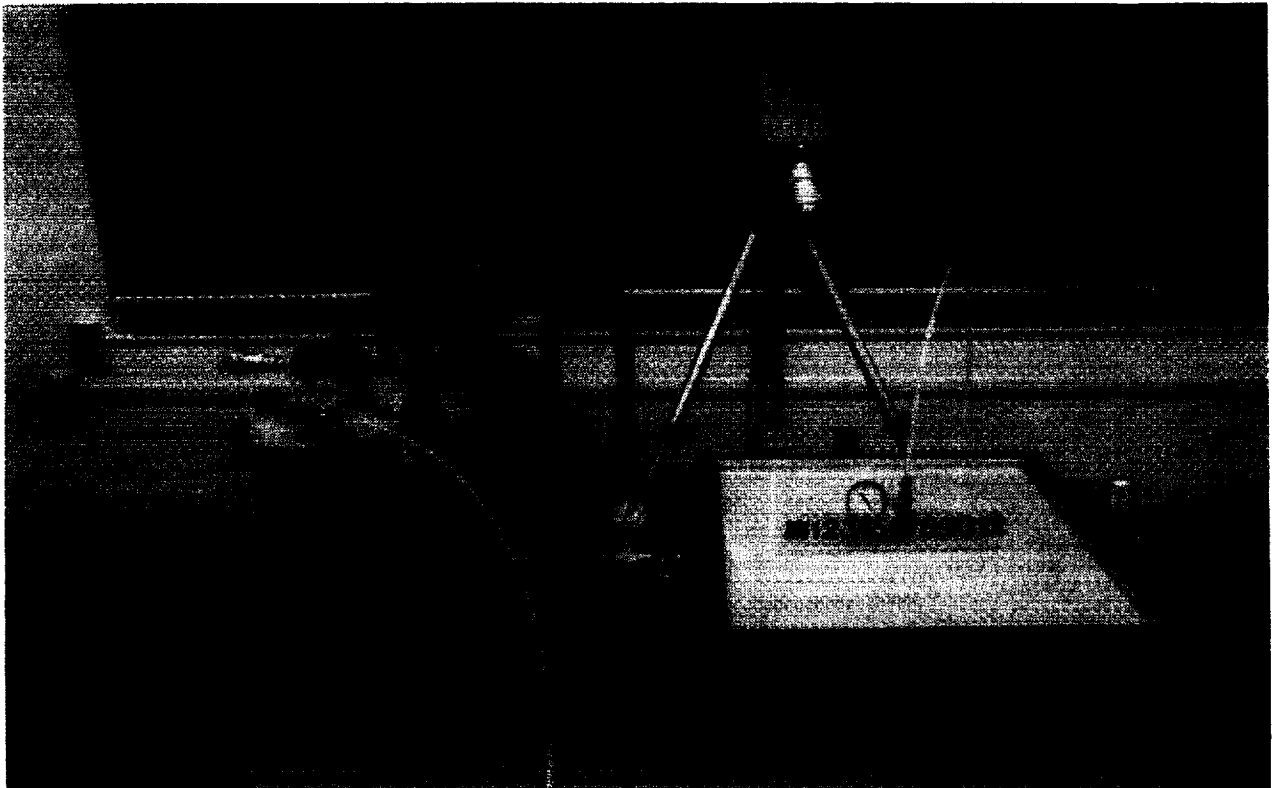


Figure 9

VERIFICATION OF RTM MODEL AND FDEMS SENSOR

Flow visualization experiments were conducted to compare predicted resin flow fronts with measured flow fronts. To enhance visualization, a fiberglass fabric with corn oil and red dye were used in the initial experiments. The viscosity of the oil and dye mixture was measured to be 40 cp. Test results are shown in figure 10 for a center port injection at an injection time of 30 seconds. An overlay of the predicted flow front and the sensor locations are also shown in the figure. Test results indicate that sensor number 4 wet-out at 27 seconds which is in close agreement with the flow front prediction. Additional experiments are underway to verify analytical predictions for aerospace grade RTM resins.

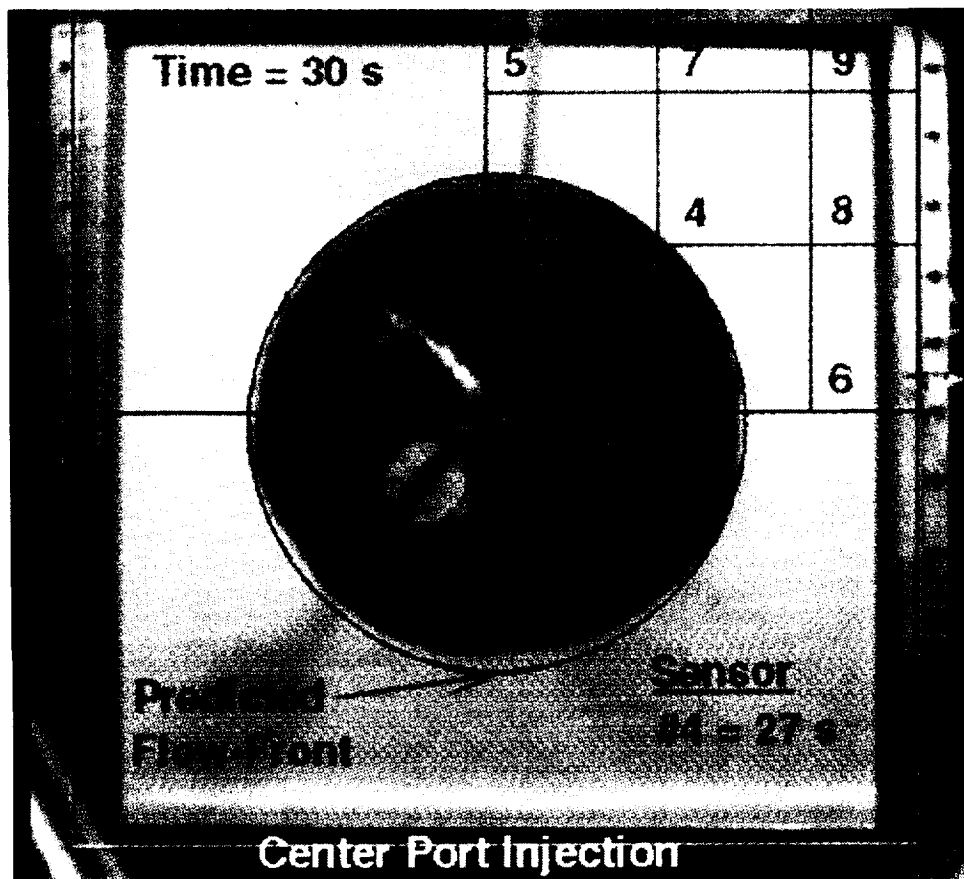


Figure 10

POWDER-COATED TOWPREG TECHNOLOGY FOR TEXTILE REINFORCED COMPOSITES

NASA Langley is conducting in-house research and is sponsoring grant and contract research to advance powder-coated towpreg technology. The objective of this research is to develop powder-coated towpreg technology as a viable alternate to RTM for fabrication of textile reinforced composites. The approach outlined in figure 11 includes optimization of the process, verifying the capability to weave and braid complex preforms, understanding compaction (bulk factor) and consolidation issues, and fabrication high quality structural elements. BASF and Lockheed Aeronautical Systems Company are key participants in an effort to scale-up the process for production applications. Three-dimensional woven panels and braided frames are being fabricated to assess the viability of the powder-coated towpreg process.

- **Objective:**

- **Develop powder-coated towpreg technology as a viable alternate to RTM for fabrication of textile reinforced composites**

- **Approach:**

- **Optimize coating processes**
- **Verify capability to weave and braid preforms**
- **Conduct compaction/consolidation studies**
- **Fabricate panels and frames and evaluate structural performance**

Figure 11

POLYMER POWDER RESEARCH

Some of the powders and product forms that are being investigated in the NASA LaRC program are listed in figure 12. Four different epoxy powders and two polyarylene ether powders are being investigated for subsonic commercial transport applications. Several polyimide and bismaleimide powders are being considered for application to future high-speed civil transport aircraft. The uniformity of powder deposition is indicated in the photograph of powder prepreg. Eight harness satin fabric that was woven with powder-coated towpreg is shown in the lower left of figure 12. Processing/consolidation studies are underway with this fabric. Mechanical properties will be compared with properties obtained with conventional prepreg fabric.

Some of the powder-coated product forms that are being investigated include uniweave prepreg tape, woven broadgoods, 2-D/3-D woven and braided textile preforms, and towpreg ribbon for use in advanced tow placement machines.

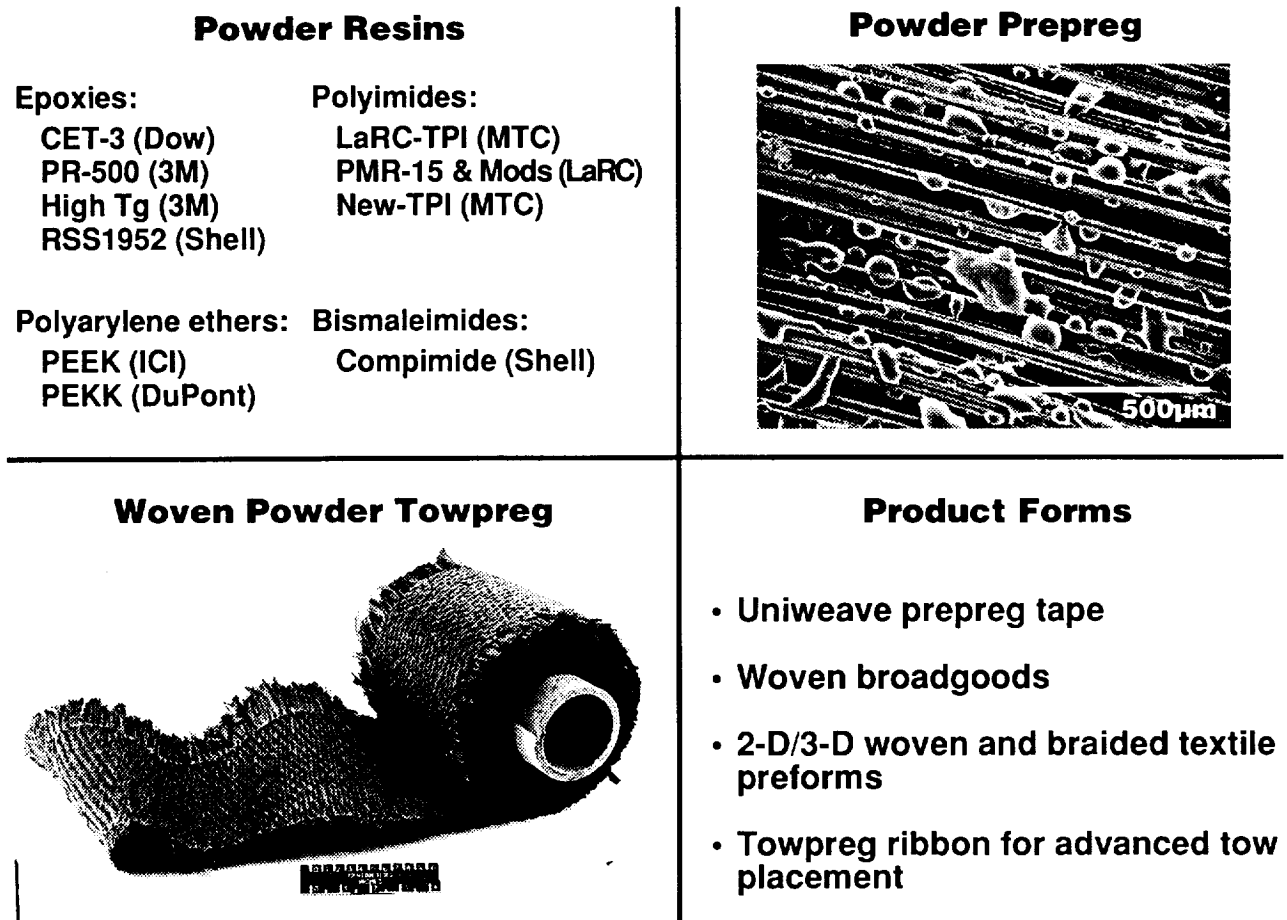


Figure 12

MECHANICS OF MATERIALS MODELS FOR TEXTILE COMPOSITES

NASA Langley has assembled a team of mechanics experts to develop methodologies and models to predict performance of textile reinforced composites. The major program elements are outlined in figure 13. An accurate description of the fiber architecture is required to adequately predict mechanical response. Mathematical formulations are being developed to describe yarn path and geometry of repeating unit cells. Stress-strain relationships will be developed from the homogeneous or continuum mechanics viewpoint. The upper right schematic in figure 13 illustrates a strategy that is mathematically similar to the finite element discretization method. Master subcells that reflect the essence of the repeating geometry are arranged in the pattern necessary to model the unit cell. The stiffness matrix for the unit cell is computed by standard matrix manipulations of the stiffness matrices of the master subcells. This type of model may be used to directly define the A, B, D coefficients or to calculate effective elastic moduli by imposing the correct boundary conditions on the unit cell.

Continuum level strength models will be developed in conjunction with the stress-strain models. This will allow a first approximation of load carrying capacity to be obtained from the average stresses computed by a global structural analysis using the homogenized stiffness properties. The average stresses will then be evaluated in a tensor polynomial failure criterion, for example, using phenomenological strength parameters determined from simple coupon tests.

A methodology will be developed to predict damage progression and residual strength using global/local analysis strategies to address damage tolerance requirements. Initial emphasis will be on modeling impact damage. Fatigue behavior will be experimentally characterized and then treated analytically. Fatigue life prediction methodologies will be developed for in-plane tension and compression loads and for out-of-plane loads.

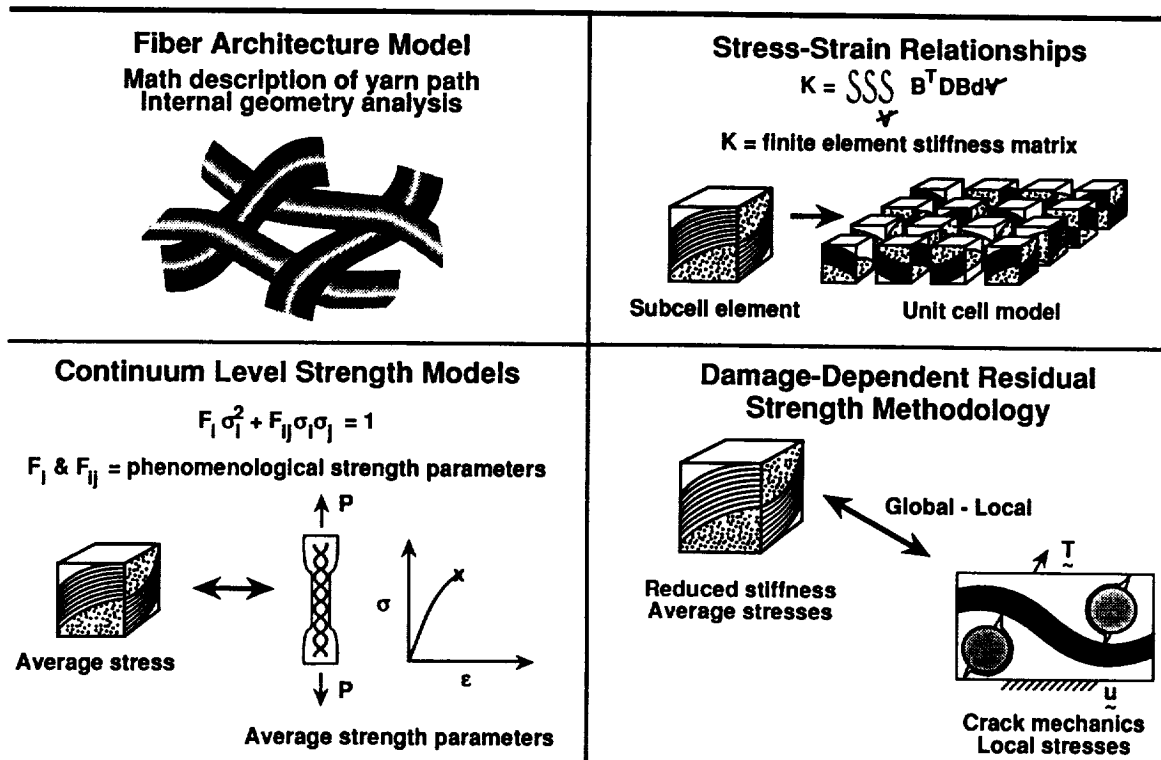


Figure 13

EXPERIMENTAL CHARACTERIZATION AND PRELIMINARY DESIGN PROPERTIES

An experimental characterization program is underway at NASA Langley to develop mechanical properties, damage tolerance, and preliminary design properties for textile reinforced composites. The objectives and program elements are shown in figure 14. Materials being characterized include woven, braided, knitted, and stitched fiber architectures. Most of the tests conducted to date have focused on in-plane mechanical properties and impact damage tolerance. A limited amount of fatigue tests have been conducted under compression-compression constant amplitude loading. Additional fatigue tests that include tension-tension and tension-compression cyclic loading are being conducted. Bearing and out-of-plane strength tests are also being conducted to assess material performance. Structural element level tests such as crippling, stiffener pull-off, and panel buckling will be expanded in the near future. Special fixtures and load introduction techniques will be developed as necessary. These tests will provide preliminary design properties and a database for comparison with analytical models.

- **Objectives**
 - **Develop experimental data base to characterize the mechanical behavior and damage tolerance of selected textile architectures**
 - **Develop preliminary design properties to support design of selected structural elements and subcomponents**
- **Program elements**
 - **In-plane mechanical properties data base for woven, braided and knitted/stitched composites**
 - **Out-of-plane strength and delamination resistance**
 - **Impact damage tolerance and notch effects**
 - **Bearing/mechanical fasteners**
 - **Tension and compression fatigue response**
 - **Preliminary design properties for specific structural elements and subcomponents**

Figure 14

TEST SPECIMENS

The test specimens that are currently being used in the NASA Langley in-house test program are shown in figure 15. The specimens have a nominal thickness of 0.250 inch with length and width as indicated in the sketches. Test results obtained to date indicate that strain gages must be selected to match particular fiber architectures. Factors such as tow size, tow spacing, and textile unit cell dimensions must be accounted for in making strain measurements. For example, a material braided with 3K tows will have a smaller unit cell than a material braided with 12K tows. The local strain response of these materials may be different, and different size strain gages may be required to accurately measure material response. Strain gages that are located directly over a through-the-thickness stitch could be affected by local material response. The size and location of resin pockets could also affect local material response. Additional research on development of standard test methods for textiles will be discussed in a subsequent figure.

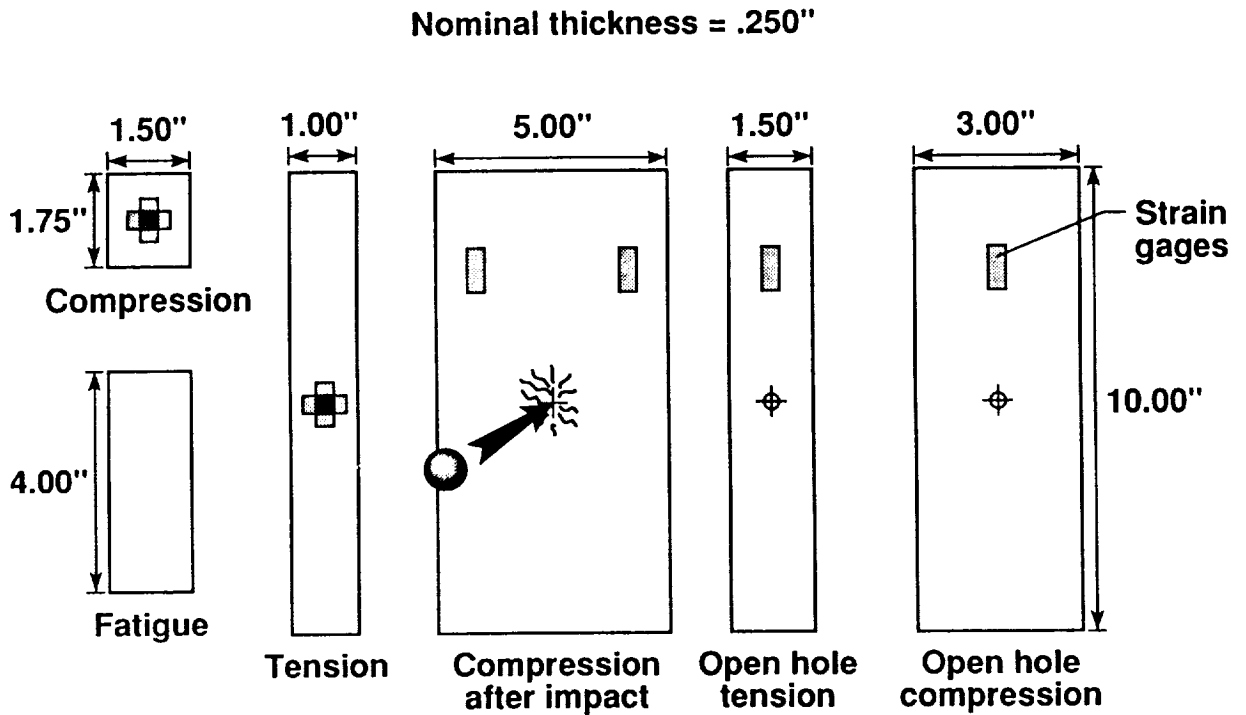


Figure 15

MULTIAXIAL WARP KNITTING CONCEPTS

Several multiaxial warp knitting concepts are being investigated at NASA Langley. Two concepts for aerospace grade carbon fabrics are shown in figure 16. Equipment is available at Milliken and Hexcel to produce the fabric concepts indicated in the figure. The Milliken fabric is knitted on a Mayer multiaxial warp knitting machine that spaces the carbon fiber tows leaving gaps that allow the knitting needles to pass through the fabric without damaging the carbon tows. As indicated in the figure, a chain knit is used.

Hexcel fabrics were knitted with both chain and tricot knit styles, as shown in the figure. The tricot knit is required to hold 0-degree tows on the surface of the fabric. The Hexcel fabric is knitted on a Liba multiaxial warp knitting machine that does not provide gaps for the knitting needles to pass through the fabric. As a result, the knitting needles impale and damage the carbon fiber tows as they pass through the fabric. Fiber misalignment is caused by the needle penetration and lack of tension on the carbon tows. The tradeoff in the two knitting methods is between fiber damage and misalignment and fiber volume fraction. The Mayer machine produces a fabric with less fiber damage but has a lower as-fabricated fiber volume fraction. Fiber volume fractions of over 60 percent have been achieved with the Milliken fabric but a consolidation pressure of well over 100 psi is required to spread the fibers and close the gaps between the carbon tows. Another knitting company, Saerbeck, that can produce high quality knitted carbon fabrics, utilizes a second generation Liba machine. Saerbeck has developed improved procedures to control tension on the carbon fibers during the knitting process.



Figure 16

PHOTOGRAPHS OF KNITTED FABRICS

Photographs of the Hexcel, Milliken, and Saerbeck knitted fabrics are shown in figure 17. The Hexcel (+45, 0, -45, 90) chain knitted fabric shown in the upper left of the figure indicates significant gaps and fiber misalignment in the surface tows. Also, some fiber damage can be seen where the knitting yarns penetrate through the fabric. The Milliken (-45, +45, 0, 90) chain knitted fabric shown in the upper right of the figure indicates uniform gaps and minimal misalignment.

The Hexcel (0, -45, 90, +45) tricot knitted fabric has significant gaps between the 0-degree surface tows, whereas the Saerbeck (0, +45, 90, -45) fabric photograph indicates only small gaps between the 0-degree surface tows. However, some slight fiber waviness is evident in the Saerbeck fabric. The gaps in all the fabrics are potential sites for resin pockets to form during the resin transfer molding process. These resin pockets can contribute to the formation of microcracks in the cured composite.

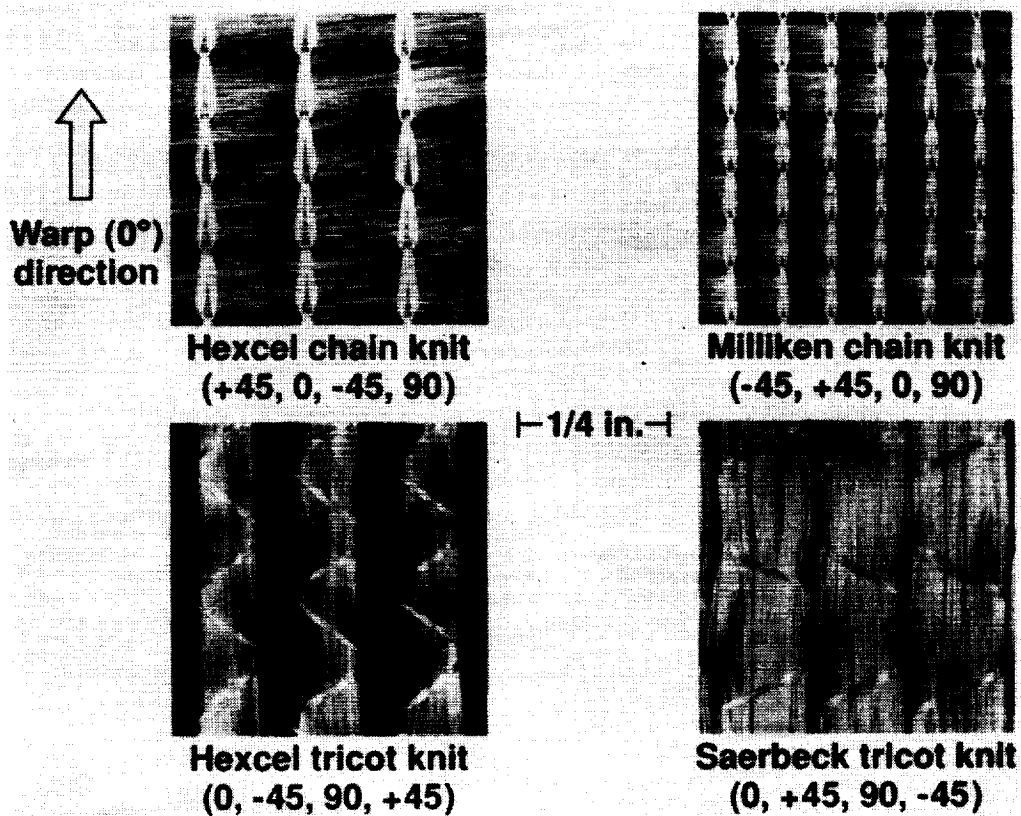


Figure 17

COMPRESSION STRENGTH OF KNITTED FABRIC COMPOSITES

The compression strengths of the Hexcel and Milliken knitted fabric laminates are compared with the strength of prepreg tape laminates in figure 18. Results indicate that the average compression strength for the Hexcel knitted fabric laminates is about 25 percent lower than the strength for the prepreg tape laminates. The Milliken knitted fabric laminates indicate a 20 percent reduction in compression strength compared to the prepreg tape laminates. These reductions in strength are partially attributed to fiber waviness caused by gaps in the knitted fabrics. No significant differences in compression strength were indicated between 3, 6, or 12K tows for the Hexcel knitted fabric laminates, or between the two resin systems used in either knitted laminates. These results indicate that significant cost savings can be achieved by using the larger tow sizes since fewer layers are required for thickness build-up and the larger tow sizes cost less per pound compared to the smaller tows.

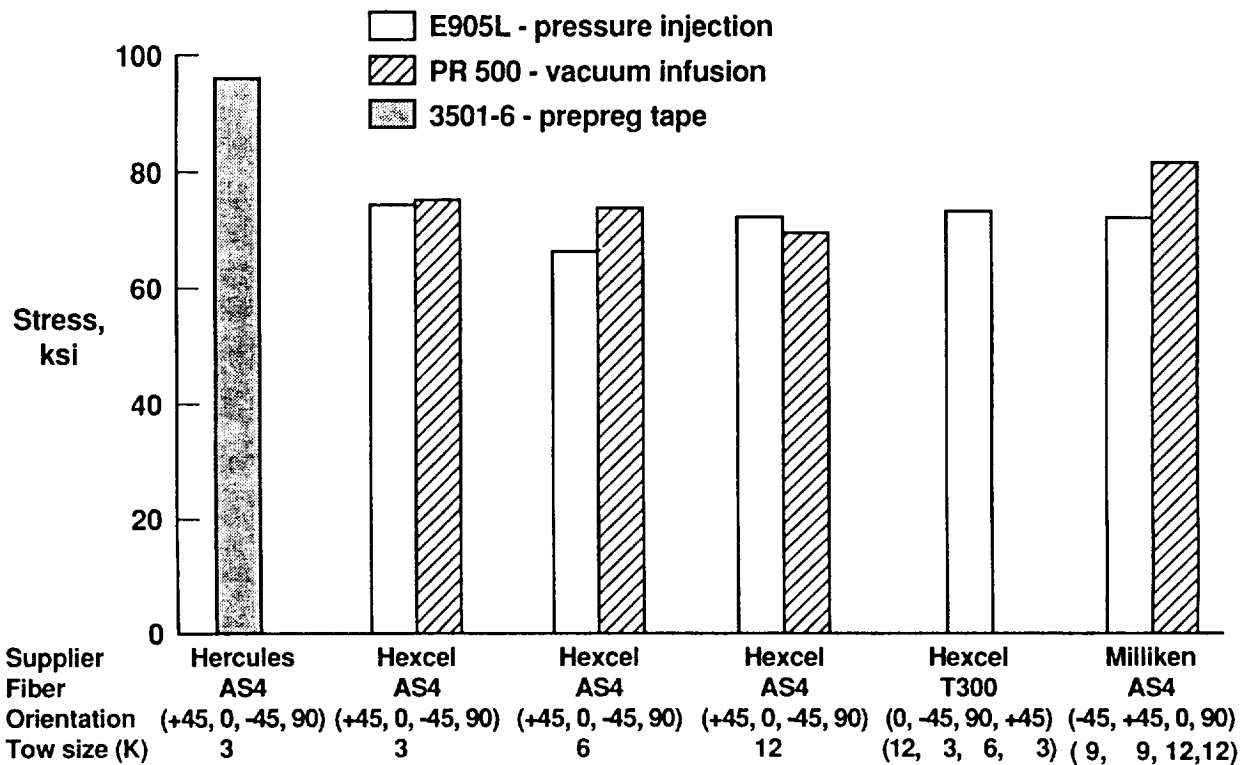


Figure 18

COMPRESSION AFTER IMPACT STRENGTH OF KNITTED FABRIC COMPOSITES

Compression after impact (CAI) strength tests were conducted to compare the damage tolerance of knitted fabric laminates with conventional prepreg tape laminates. The 1/4-inch thick laminates were impacted with 1/2-inch diameter aluminum spheres at an impact energy of 30 ft-lbs with the NASA Langley air gun. The test results shown in figure 19 indicate that the knitted fabric laminates that were resin transfer molded with the toughened PR 500 resin had CAI strengths up to 50 percent higher than the brittle 3501-6 prepreg tape laminates. The knitted fabric laminates with E905L resin had CAI strengths that were up to 30 percent higher than the prepreg tape laminates. These results indicate significant improvements in damage tolerance for the knitted fabric laminates. However, they still fall well below the target of 40 ksi, desirable for airframe structural applications. Additional through-the-thickness reinforcement such as heavy density stitching is required to achieve the target value.

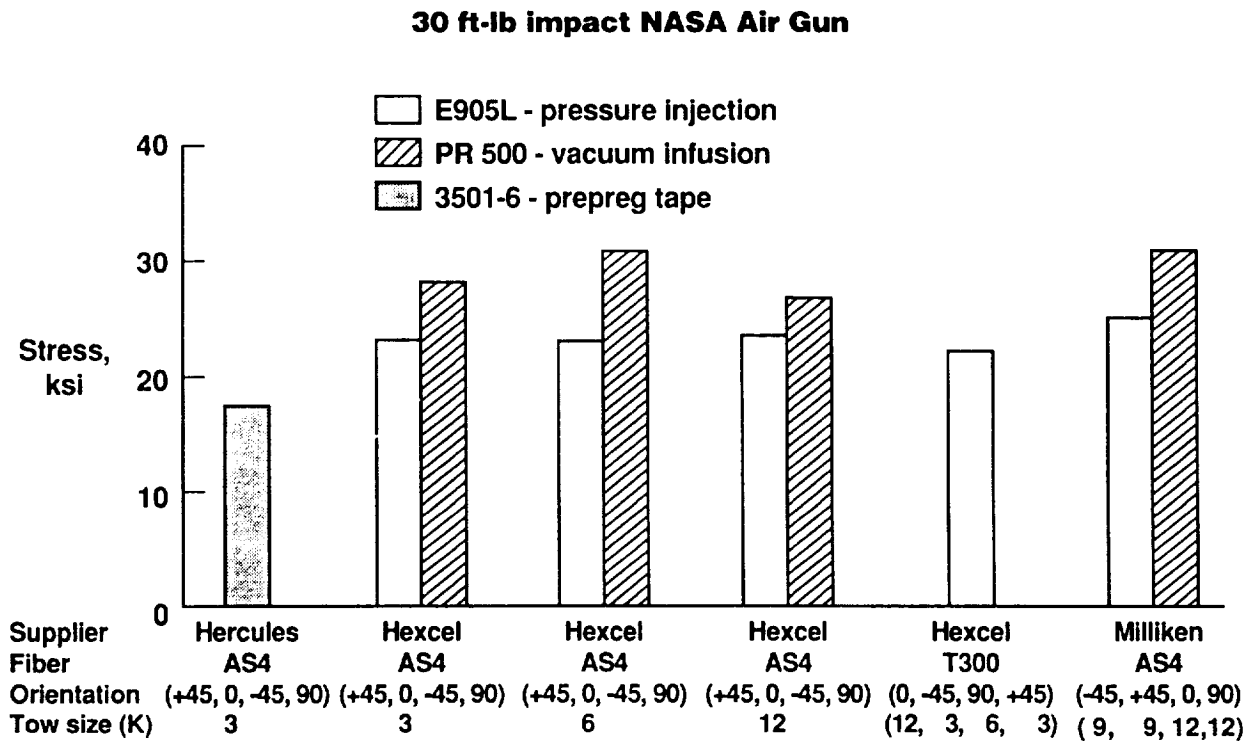


Figure 19

COMPRESSION AFTER IMPACT STRENGTH OF KNITTED/STITCHED FABRIC COMPOSITES

Compression after impact strength tests were also conducted to determine the effect of stitching on the strength of knitted fabric laminates, figure 20. The Hexcel preforms that were knitted with 3K and 12K tows were stitched by Ketema with a modified lock stitch. The preforms were stitched in the 0-degree direction in columns 0.33-inch apart with a stitch pitch of 1/8 inch. The Milliken preforms were stitched by Puritan Industries with a chain stitch. The panels were chain stitched in the 0-degree and 90-degree directions with rows and columns 1/4-inch apart with a stitch pitch of 1/8 inch. All the preforms were stitched with a 1500 denier Kevlar thread.

The panels were impacted at an energy level of 30 ft-lbs with the same procedure described earlier. The Milliken knitted/stitched fabric laminates with the PR 500 resin system achieved the target of 40 ksi CAI strength. The Hexcel knitted/stitched laminates fell below the target. The toughened PR 500 resin system exhibited consistently higher CAI strengths than the E905L, as was noted in the unstitched results. Results of a previous stitching study, reference 1, indicated strengths over 45 ksi with stitched uniweave fabric laminates when a stitch spacing of 3/16 inch was used. Based on those findings, it is expected that the Hexcel fabric laminates would achieve the target value if the stitch spacing was reduced to no more than 3/16 inch. Additional details on test results for knitted fabrics are reported in reference 2.

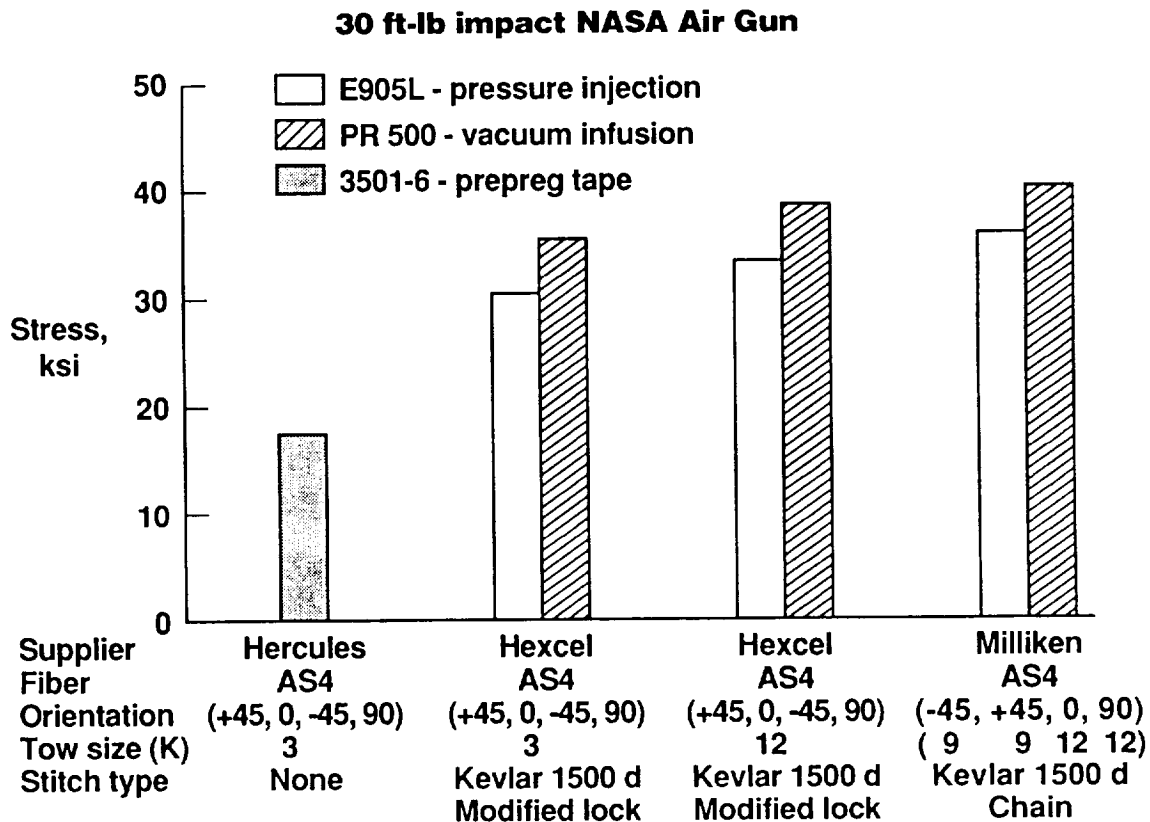


Figure 20

PERFORMANCE COMPARISON OF AS4/PR500 SAERBECK KNITTED AND UNIWEAVE FABRIC COMPOSITES

Douglas Aircraft Company and NASA Langley have been developing a data base on uniweave fabrics for application to wing structural components. The Douglas design for the wing skin material consists of 54 plies of uniweave fabric with 44 percent of the fibers in the 0-degree direction, 44 percent of the fibers in the ± 45 -degree directions, and 12 percent of the fibers in the 90-degree direction. Concerns for stability and the ability to handle large pieces of the uniweave fabric led Douglas to investigate other fabric options. A knitted fabric produced by Saerbeck in Germany was selected. A description of the fabric was discussed earlier. The test results presented in figure 21 were developed at NASA Langley in a cooperative effort with Douglas. It should be noted that the test results are preliminary and additional tests are planned to expand the data base.

Tension, compression, open hole tension, open hole compression, and CAI tests were conducted to compare the performance of the knitted and uniweave fabric laminates. All of the fabrics were resin transfer molded with the 3M PR 500 resin except the stitched uniweave CAI panel which was fabricated with Hercules 3501-6 resin. Also, the uniweave panel was stitched with S-2 glass whereas the Saerbeck panel was stitched with Kevlar. The stitched uniweave panel was impacted at an energy level of 40 ft-lbs with a drop weight apparatus. The other panels were impacted at an energy level of 30 ft-lbs with the air gun previously described. Test results shown in figure 21 indicate comparable performance between the two fabrics. Both fabrics meet the design requirements for the Douglas wing skin. It should be noted that the Saerbeck knitted fabric consisted of six 4-ply stacks whereas the uniweave fabric consisted of 54 plies to build up the required thickness of 0.30 inch. This difference has important cost implications in terms of labor savings.

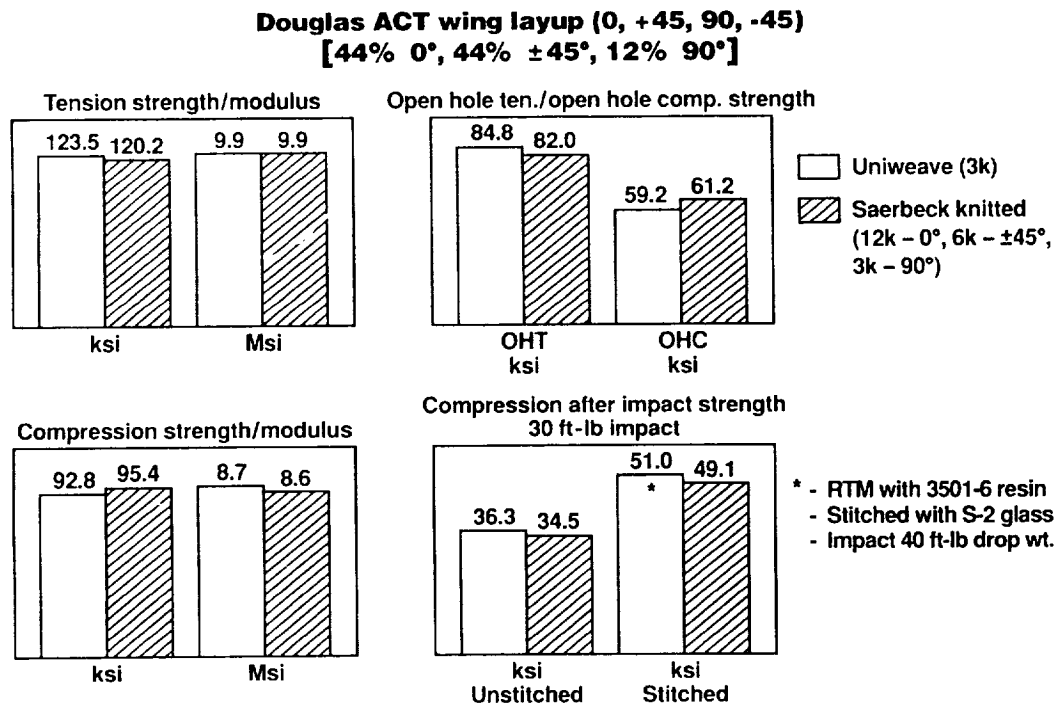


Figure 21

COMPRESSION AND COMPRESSION-AFTER-IMPACT STRENGTH OF BRAIDED COMPOSITE PANELS TESTED IN THE 0° DIRECTION

Compression and compression-after-impact (CAI) strengths of 2-D braided, 2-D braided/stitched, and 3-D braided composites are compared in figure 22. The braided preforms were fabricated with AS4 carbon fibers with a ($\pm 30/0$) fiber architecture. The preforms were infiltrated with British Petroleum E905L epoxy resin. An impact energy of 30 ft.-lbs was used to impact the panels, which had nominal thicknesses of 0.24 inch.

Test results indicate that the 3-D braided panels had the highest undamaged strength, over 60 ksi, whereas the 2-D braided/stitched panels had the highest CAI strength, over 40 ksi. It is somewhat surprising that the CAI strength for the 3-D braided panels was only slightly better than the CAI strength for the 2-D braided panels which have no through-the-thickness reinforcement. Additional testing is underway to further understand the behavior of braided materials. Additional details on braided test results are reported in reference 3.

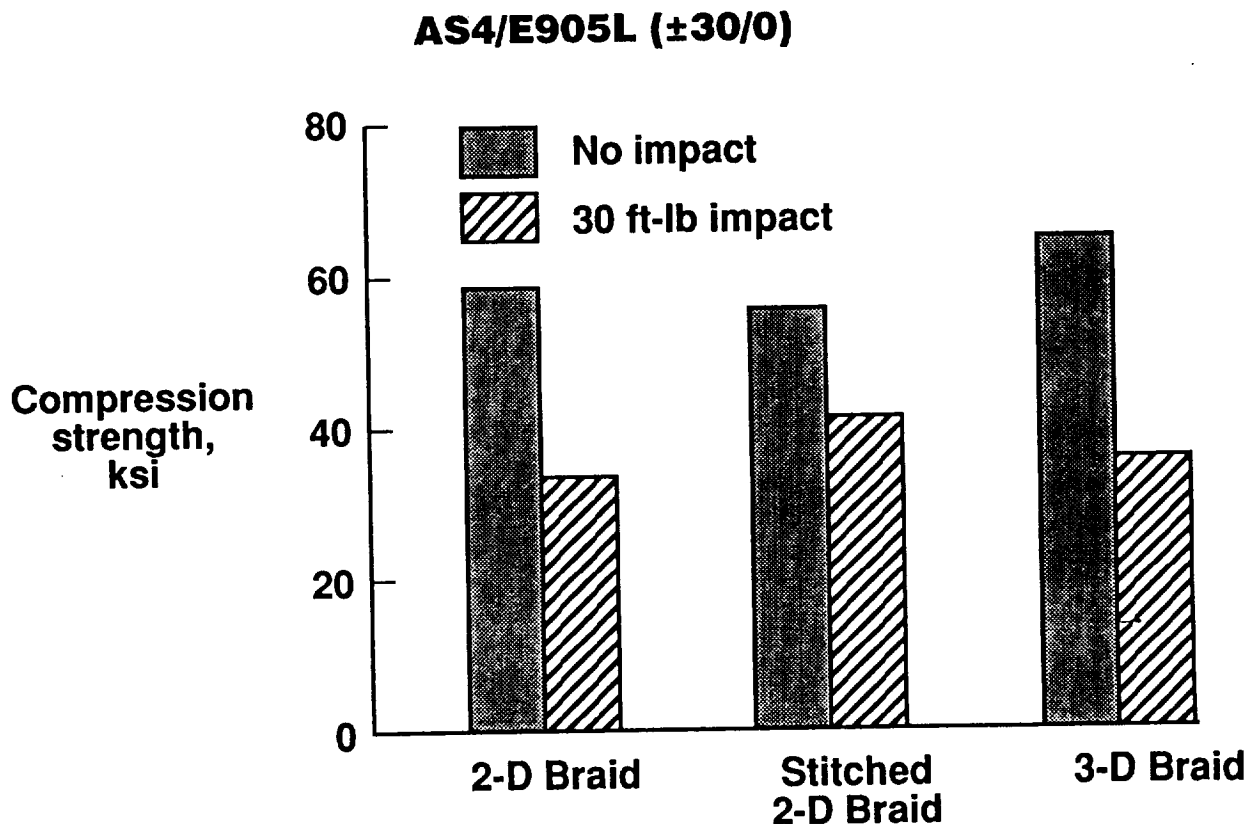


Figure 22

STANDARD TEST METHODS FOR TEXTILE REINFORCED COMPOSITES

New test techniques will be required to characterize some of the unique properties of textile reinforced composites. The sketches shown in figure 23 indicate some of the types of tests that must be conducted to explore the benefits of textile material forms. Some of the currently used in-plane test methods may be adequate for textile materials. However, modification of specimen dimensions and strain measurement techniques may be required for some textile architectures. The effect of textile unit cell dimensions on mechanical behavior must be characterized. Since textile materials with through-the-thickness reinforcement offer significant improvement in out-of-plane load capability, adequate test methods must be developed to assess performance improvements. Subelement level tests such as stiffener pull-off must also be developed. Analytical studies, in conjunction with experiments, must be performed to assure that stress states are understood and that local effects are representative of global material response. Available standard test methods in the composites industry will be investigated and used where appropriate.

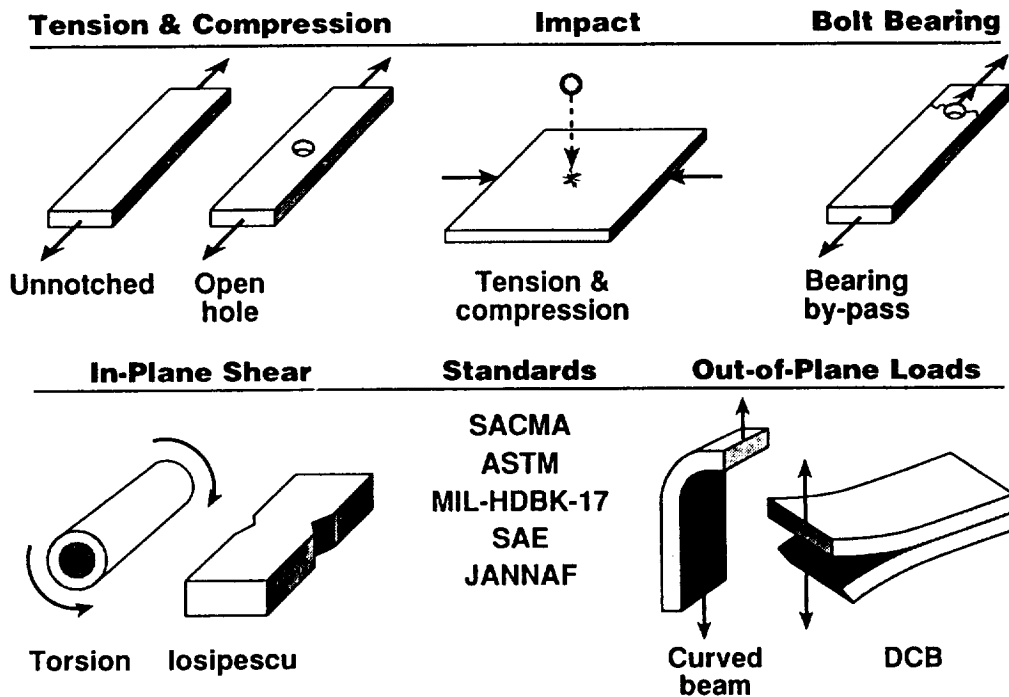


Figure 23

TEXTILE REINFORCED COMPOSITE FUSELAGE SUBCOMPONENTS

As part of the ACT program, specific fuselage subcomponents were selected as candidates for application of textile material forms. Based on discussions between NASA Langley, Lockheed, Grumman, and Boeing, the four subcomponents shown in figure 24 were selected. These structural subcomponents were selected to exploit damage tolerance and through-the-thickness strength capability of textile materials. Structural tests will be conducted on each structural subcomponent to verify the performance of textile architectures. Analytical predictions will be performed and results will be correlated with experimental behavior.

Particular design issues associated with each subcomponent are indicated in figure 24. Several textile processes such as integral weaving, braiding, knitting, and stitching are being used to produce near net-shaped structural subcomponents. Some obvious candidates include continuously braided circumferential frames, integrally woven stiffened panels, and stitched reinforcement around window openings. An integrated design-build-team effort is being conducted by Boeing, Lockheed, and Grumman. This is necessary since some of the subcomponents will be delivered to Boeing for test in their fixtures. Additional test articles will be delivered to NASA Langley for testing in new combined load machines/fixtures that are under development.

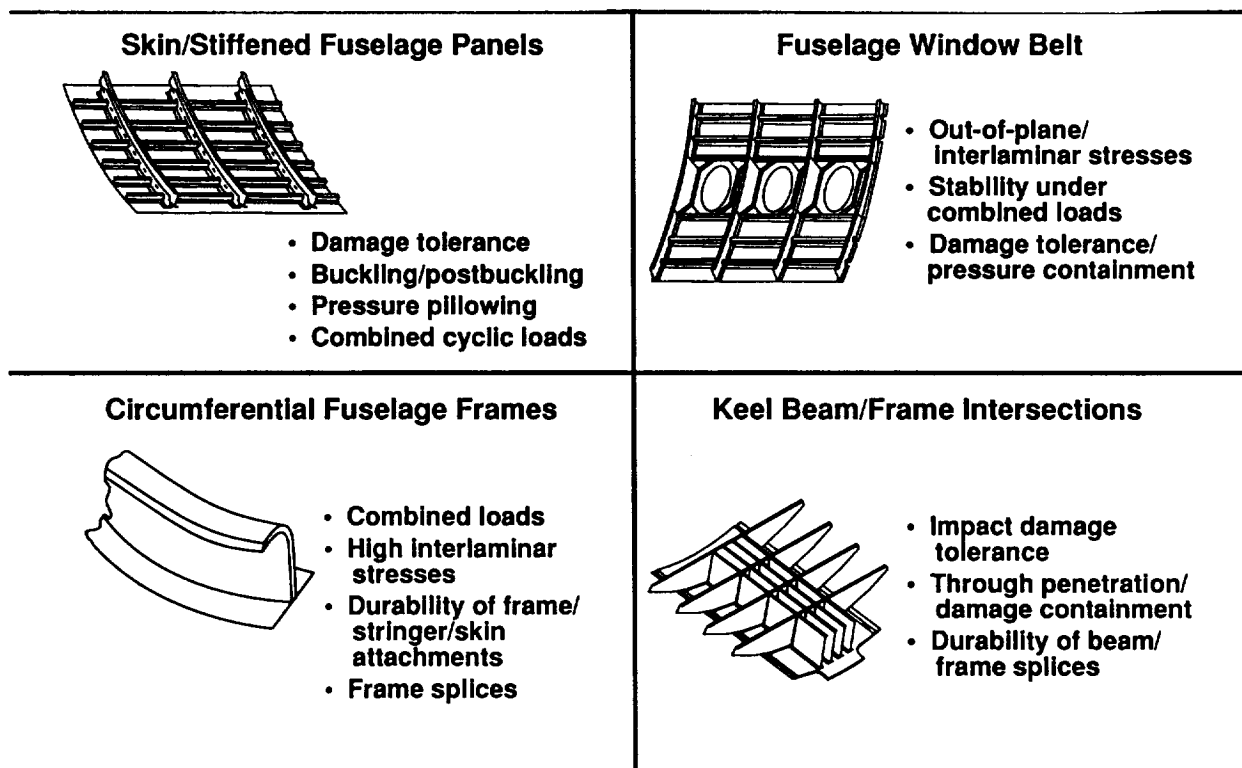


Figure 24

WOVEN/STITCHED WINDOW BELT PREFORM

As discussed previously, Grumman is conducting research on textile preforms for applications to fuselage structures. The fuselage window belt is an area of the fuselage that has complex loading states and is a good candidate for textile reinforced composites with through-the-thickness reinforcement. The window belt preform shown in figure 25 was designed by Grumman and fabricated by ICI Fiberite. The cross-stiffening elements were integrally woven in one piece with IM7 carbon fibers. The 0-degree fibers along the webs of the stiffening elements are continuous through the intersections. To achieve the necessary shear stiffness for the stiffeners, ± 45 -degree woven fabric was laid up over the stiffener elements and subsequently stitched onto the skin through the stiffener flanges with Kevlar thread. The window belt preform will be resin transfer molded by R-Cubed Composites. The window cut-outs will be machined away prior to shear testing by Grumman.

A second preform is being fabricated by Textile Technologies, Inc. and Fiber Innovations, Inc. This preform will be fabricated with 2-D braiding in the stiffening elements and 2-D weaving in the skin. The preform will be fabricated with AS4 carbon fibers and Kevlar stitching.

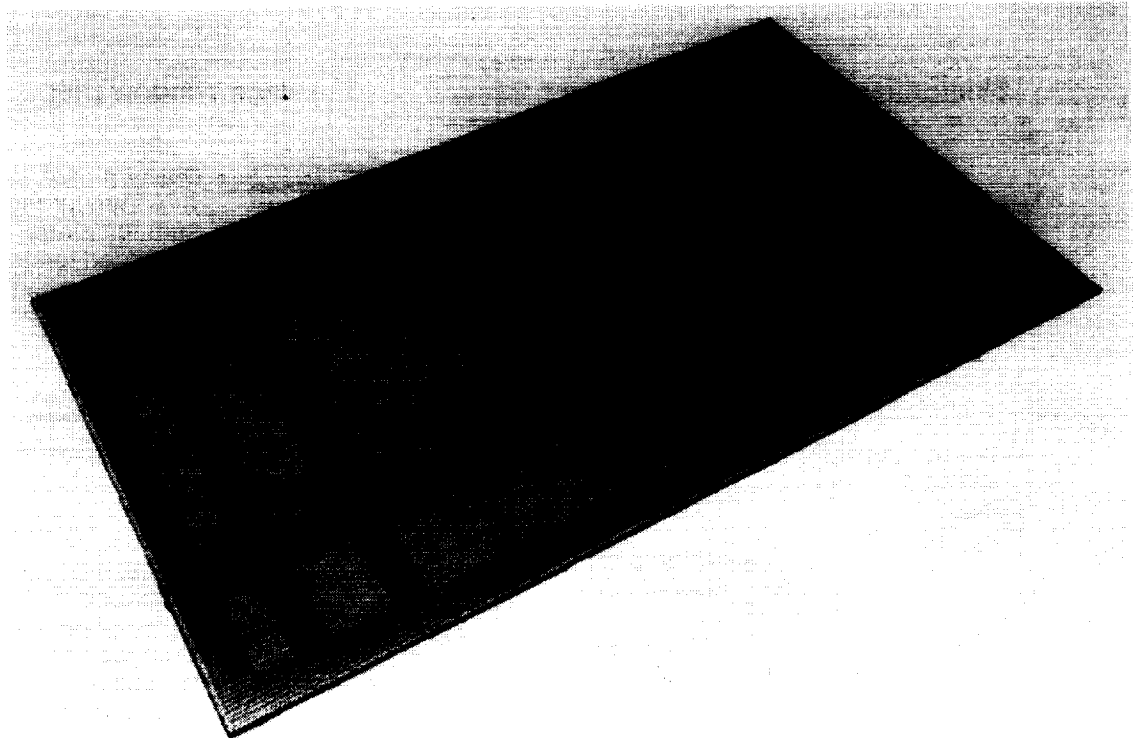


Figure 25

3-D BRAIDED F-FRAME

Previous studies have demonstrated that braiding is an excellent textile process to develop preforms for complex structural shapes. As part of the NASA ACT program, Lockheed Aeronautical Systems company is conducting research on textile reinforced composites for aircraft fuselage structural applications. The braided F-frame shown in figure 26 was designed by Lockheed and Atlantic Research Corporation. The design included some innovative bifurcation concepts that allowed the preform to be split open to achieve the F-configuration. The frame was braided by Atlantic Research on an automated 3-D braiding machine. The major advantage of the 3-D braiding process is that one-piece, near net-section preforms with through-the-thickness fibers can be fabricated. The preform shown in figure 26 was braided in a rectangular box which was subsequently split to achieve two preforms. The preform was resin transfer molded by Lockheed with a resin injection pump and a fixed cavity mold.

Preform and RTM Composite

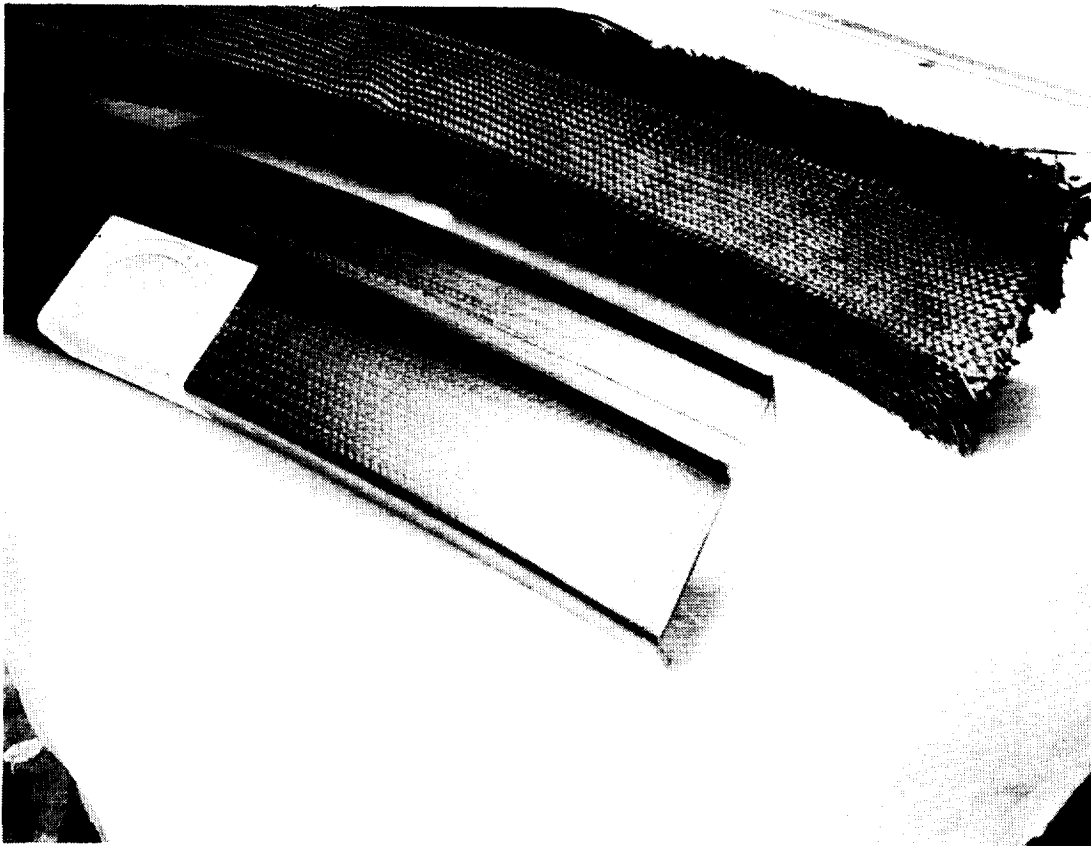


Figure 26

WINGBOX CRITICAL TECHNOLOGY ISSUES

Critical technology issues that must be solved to achieve widespread application of textile reinforced composites in transport wing components are indicated in figure 27. As part of the NASA ACT program, Douglas Aircraft Company is conducting research to address these critical issues. The major focus is on development of damage tolerant structural concepts and cost-effective fabrication processes. Program emphasis is on stitched preforms and resin infusion processes. Material level coupons and test panels have been fabricated and tested to demonstrate the damage tolerance characteristics of stitched composites. Through-the-thickness resin infusion processes have been developed as a cost-effective method to infiltrate resin into the structural preforms. Stiffened panel tests are underway to demonstrate the structural performance of woven/stitched composite materials. Larger wingbox components will be fabricated in the next phase of the program to address some of the scale-up issues associated with fabrication of woven/stitched composites.

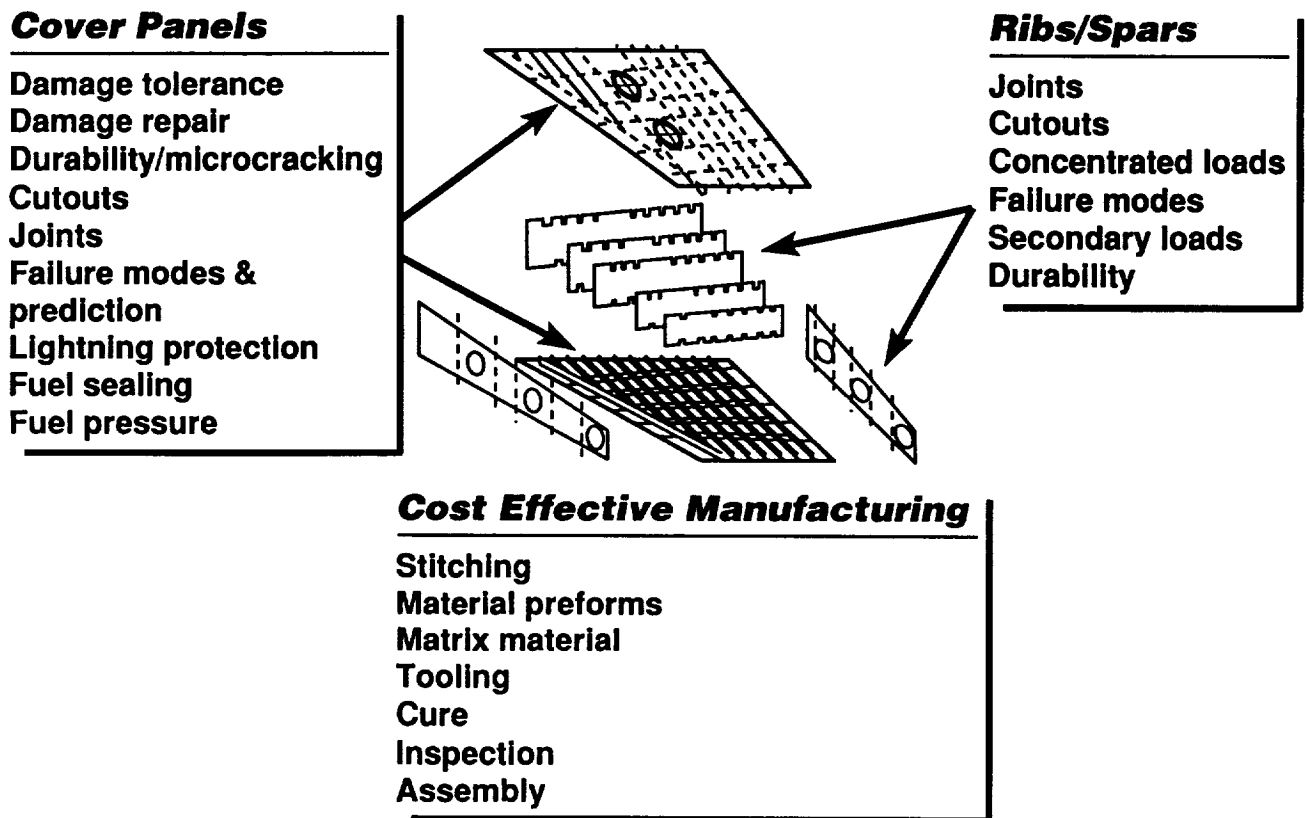


Figure 27

UNIWEAVE/STITCHED WING PANEL

A four-stringer woven/stitched wing panel that was fabricated by Douglas Aircraft Company is shown in figure 28. The AS4/3501-6 panel also has two integral rib attachments that are stitched onto the skin. This panel was fabricated by stacking layers of unidirectional woven fabric (uniweave) to the desired thickness and stitching the layers together. The stiffeners and rib attachments were laid up in a similar manner and subsequently stitched to the skin. The preform was placed in a tool, resin was infused into the preform, and the panel was cured in an autoclave. Panels of this type are being fabricated by Douglas to demonstrate fabrication technology and to develop a data base on structural response of woven/stitched composite materials.

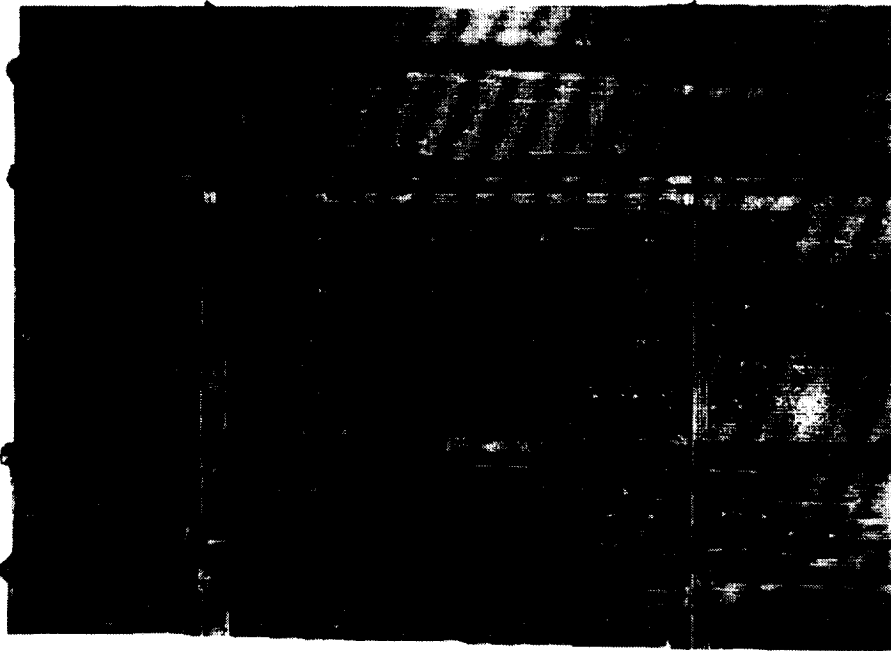


Figure 28

CONCLUDING REMARKS

Redirection of some of the NASA ACT contracts on textile reinforced composites has provided an aircraft structures focus to the NASA Langley textile composites program. Textiles are being applied to specific structural elements where textiles offer a clear advantage over more conventional material forms. The NASA Langley textile reinforced composites program is addressing some of the key technology issues associated with the use of these relatively new material forms. Engineering design guidelines and performance requirements for application of textiles to aircraft structures will be established. Analytical models will be developed to predict material behavior and structural performance.

New NDE-based process/quality control methods must be developed for textile preforms and composites. Real-time feedback controls must be developed to assess quality during the fabrication process to eliminate undue scrap. Processing and fabrication studies that focus on science-based understanding of processing parameters and tooling concepts will be accelerated. Trial-and-error processing studies that have been conducted in the past are too costly and must be minimized. New test methods are required to establish an accurate assessment of textile material performance. Design property databases for applicable textile material forms must be generated so that designers can conduct accurate trade studies.

Structural elements and subcomponents that exploit the full potential of textile material forms will be designed, fabricated, and tested. An integrated team that includes textile preformers, structural designers, analysts, process engineers, and tool designers has been established to work together for cost-effective structural application of textile materials.

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