CROSS-STIFFENED CONTINUOUS FIBER STRUCTURES

JOHN R. EWEN
GRUMMAN AIRCRAFT SYSTEMS
BETHPAGE, NEW YORK

JIM A. SUAREZ
GRUMMAN AIRCRAFT SYSTEMS
BETHPAGE, NEW YORK

SUMMARY

Under NASA's Novel Composites for Wing and Fuselage Applications (NCWFA) program, Contract NAS1-18784, Grumman is evaluating the structural efficiency of graphite/epoxy cross-stiffened panel elements fabricated using innovative textile preforms and cost effective Resin Transfer Molding (RTM) and Resin Film Infusion (RFI) processes. Two three-dimensional woven preform assembly concepts have been defined for application to a representative window belt design typically found in a commercial transport airframe. The 3D woven architecture for each of these concepts is different; one is vertically woven in the plane of the window belt geometry and the other is loom woven in a compressed state similar to an unfolded eggcrate. The feasibility of both designs has been demonstrated in the fabrication of small test element assemblies. These elements and the final window belt assemblies will be structurally tested, and results compared.

INTRODUCTION

Several attempts have been made to provide structural continuity through the intersection of cross-stiffened graphite composite structure. Initial attempts included bonding metal cruciforms to the graphite stiffeners at the intersection and alternately placing unidirectional tows across the intersection. Adaptations of tow placement have been successfully tried using syntactic foam to accommodate the cross intersection lay buildup. These methods and others have met with varying degrees of success. The primary focus of all of these innovative concepts was to improve the composite structure load-carrying capability through the cross-stiffened intersection.

It was recognized that an effective solution was necessary to further advance the utilization of advanced composites in airframe structures. Successful application of cross-stiffening would permit designs that could, until this time, only be effectively achieved with metallic designs. Efficient, supportable, and affordable graphite solutions would permit more effective composite applications for airframe components such as bulkheads, doors, window belts, and skin panels. Essentially, any cross-ribbed structure is a potential candidate.

The resulting benefits for developing such a capability are reduced weight, improved material utilization, reduced number of parts, and a potential for reduced costs.

With the technology development and introduction of three-dimensional textile weaving and braiding processes, new opportunities became available to present solutions to this problem. Weaving technology has progressed significantly for use in structural composite applications. More importantly, these processes offer the potential to achieve continuous through-the-intersection fiber integrity with high-strength graphite fibers.

These textile processes permitted new composite material fabrication methods to be developed. Dry unimpregnated assemblies were produced by combining/stitching various textile products, such as 2D woven broadgoods, 3D woven assemblies, and braided items, to form complex shapes. These resulting textile assemblies provide preforms for subsequent processing.

In addition, processing methods have been developed that are compatible with textile preform assemblies. Resin Transfer Molding (RTM) and Resin Film Infusion (RFI) are two such methods presently being applied to the fabrication of airframe parts.

Grumman is currently under contract with NASA to develop innovative, cost-effective, damage-tolerant design concepts for airframe structure. A major task of this program is to design and demonstrate the effectiveness of a textile cross-stiffened continuous fiber structure. This demonstration will utilize advanced textile preform architectures and processing technologies to fabricate a commercial transport demonstration subcomponent. For this demonstration, the airframe part selected is a window belt typical of that found in a commercial transport. The specific reasons for this selection are: the design is generic to cross-stiffened biaxial loaded structure; it is highly loaded, carrying both fuselage bending and cabin pressure loads; it presents a fair degree of complexity; and it is a repetitive assembly along the length of an aircraft. Figure 1 depicts the area of interest, a detail of an existing metallic assembly, and an isometric of the textile subcomponent.

The remainder of this paper will discuss the technical data related to this task. This includes the requirements, component definition, materials, selection of textile process, textile preform assembly methodologies, test plan, tooling, and lesson learned.

REQUIREMENTS/CRITERIA

The design loads used to size the window belt subcomponent were obtained from Boeing Commercial Aircraft and are representative of a typical wide-body fuselage window belt region. Figure 2 displays the direction and magnitude of the ultimate design axial loads and shears for two maximum load conditions.

The fail-safe design allowable strain (80% limit) was selected to be 2400 μin./in. for this application. This is commensurate with Boeing's fail-safe allowable strain of 2000-3000 μin./in. The resulting design ultimate strain is 4500 μin./in.

The geometrical definition was also obtained from Boeing and was used as a guide to define the subcomponent. The actual fuselage side panel containing the window belt has a radius of 122 in. The subcomponent was configurated flat to reduce test costs. The window spacing is 22.00 in. and the longitudinal stiffener spacing, which frames the windows, is 19.00 in.

COMPONENT DEFINITION

The textile preform window belt subcomponent design, drawing D19B1865, is shown in Figure 3. The drawing presentation defining the composite layup is significantly different from one applied to a unidirectional or broadgoods composite design. For typical 2D composite applications, fiber orientation, number of plies, and stacking sequence can be defined exactly on the engineering drawing and, in turn, fabricated as specified. Three-dimensional woven preform assemblies, on the other hand, cannot be as simply defined because of the diversity of weaving/stitching processes, complexity of fiber orientations, yarn tow size and variation of fiber architecture.

To enable preform fabricators to exercise creative solutions, promote freedom in design, and avoid imposing adverse restrictions to a design, drawing D19B1865 stipulates target values for fiber volume and percentage of 0, 90±45 directional yarns and stitching yarns. This notation provides the freedom to develop a complex fiber architecture and preform assembly using the techniques and equipment familiar to each potential supplier. However, this method, if not concurrently engineered, can compromise the structural capability of the resulting assembly.

The geometrical definition, particularly the thickness dimensions, are called out as are net final cure dimensions. It is desirable that the preform be within 10% of this dimension to enable tooling to be effectively designed. Preforms with bulk factors as high as 200% will impose restrictions on tooling designs, with the potential to increase complexity and related costs.

The window belt subcomponent, as shown in Figure 3, is 38 in. x 62 in. and consists of two primary longitudinal members, 0.48 in. thick, six transverse stiffeners, 0.17 in. thick, and a 0./17 inc. in-plane skin. The intersections of these transverse and longitudinal stiffener members have continuous fibers through the intersection to provide structural continuity at each joint. These intersecting members are attached to the skin panel with flanges to provide a load path to transfer the panel shears to the stiffeners. The entire assembly is stitched to provide stability to the dry preform and to enhance the damage tolerance of the final article. The stitching density is to be a maximum of 6% to prevent strength degradation. Two elliptical cutouts, with a major diameter of 17.25 in., replicate the windows. The provision of through-the-intersection fiber continuity is the main focus of attention .

ANALYSIS

The subcomponent was sized using composite laminate analysis methods with adjustments for through-the-thickness reinforcement, assuming a 60% fiber volume, 4500 μin./in. allowable ultimate strain, and IM7 graphite properties. AS4 was considered as an alternate material for the subject application.

A three-dimensional NASTRAN finite-element model of a repeating section of the window belt subcomponent was constructed and is shown in Figure 4. The section consists of a single window section with three ring stiffeners and two associated longitudinal stiffeners with the adjoining skin. A complete model of the subcomponent to be tested will be comprised of two such repetitive models and a boundary region component model. The latter will also be derived from a generic boundary model.

The general window component model is represented by 1066 node points (GRID) interconnected by 1004 quadrilatral bending elements (CQUAD4). This model depicts the stiffeners as a combination of bending elements which provides for the geometric distribution of the structure and is also capable of representing the structural response of the extended stiffeners. The FEA will be used to predict strains in critical areas for the subsequent component structural tests.

MATERIALS AND PROCESSES

The principal graphite fiber material selected for this woven and stitched preform assembly is IM7. AS4 graphite was considered as an alternate material because of its lower cost, availability and widespread use. Stitching is to be performed using high-strength Toray graphite thread or Kevlar thread as an alternate. The size of the tows and yarns was left to the suppliers and was dependent on the individual weaving process.

The composite processing will be achieved using either RTM or RFI. Both processes are compatible with the preform assembly. Grumman has successfully demonstrated both the RFI and RTM methodology in the Novel Composites for Wing and Fuselage Applications program in the manufacture of "Y" spars.

The epoxy resin materials that are being considered for RTM of the window belt article include Shell 1895, British Petroleum E905L two-part systems, and 3M PR500 one-part system. The resin film material being considered for RFI of the window belt is 3501-6 epoxy.

EVALUATION CRITERIA

Evaluation criteria were established to compare the preform assemblies and textile processes that were proposed by suppliers. These criteria were based on parameters that would be necessary for a cross-stiffened design. The primary comparative evaluators were ability to provide true through-the-intersection fiber continuity, ability to provide and control the percentage and direction of yarn orientations, ability to vary the thickness of the skin panel and provide different stiffener thicknesses, and use of a process that has application for large scale-up production. Other considerations included viability of the process, cost of the final preform, and delivery schedule.

Five textile fabricators submitted proposals which described eight concepts to develop solutions for the window belt design. The designs varied and consisted of braided details, 3D woven details, stitching, and assemblies of these and 2D components. Of the five evaluated two were selected to produce the preform and related test elements. These two supplies are Techniweave, Inc., Rochester, New Hampshire and ICI Fiberite, Greenville, Texas.

The two processes are significantly different. The ICI Fiberite approach employs a conventional weaving loom with a Jacquard head to fabricate the cross-stiffeners and then attaches them to 2D woven broadgoods. The Techniweave process utilizes an integral weaving technique whereby the structural preform is achieved by interlacing graphite yarns around closely spaced pins. The primary distinguishing differences is that Techniweave can weave the stiffeners integral with the skin in the plan form of the subcomponent, whereas ICI Fiberite unfolds a loom-woven 3D cross-stiffened rib structure and assembles it to the 2D woven skin panels by using a uncatalyzed epoxy resin and stitching.

PROCESS DESCRIPTION

Techniweave Process

The Techniweave fabricated preform is an assembly consisting of a large 3D integrally woven detail and several 2D woven broadgood ply details. Figure 5 is a schematic representation of this final product. The 3D detail as shown is the predominant feature which integrates the panel skin and stiffeners, and provides the continuity of fibers through the intersection. The 2D bias broadgood plies are stitched to the stiffeners and skin panel to complete the assembly.

This 3D weaving process employed to fabricate the core detail is unique. It is a method which has been demonstrated in various thick preform assemblies made by Techniweave and others. More recently, Techniweave has developed fabrication technology for application to thin wall sections such as defined for the window belt design. Currently, it is a manual process where the weaving is done in layers following predescribed paths. Registration of successive layers is assured with the use of tooling to define through-the-thickness yarn sites. Figures 6, 7, and 8 show vertical yarn stitch sites for a 7-in. by 7-in. test element and two skin surface weave layer definitions, 0° and 45°.

Initiation of the weaving starts from the surface panel and continues vertically to build up the skin thickness and stiffener heights. The yarns are interwoven through the predescribed paths as shown in the layer diagrams, in the required orientations 0, ±45, 90. Since this is a planar process, the bias weave is easily accommodated in the skin panel but is unable to be incorporated in the stiffeners. The applied stiffener yarns consist of the 0-degree orientations that are continuous through the intersection and "Z" weaving yarns that are woven through the thickness, as shown in Figure 9.

Upon completion of this initial weaving phase, the vertical yarn sites are consecutively stitched. These yarns provide the 90-degree orientation in the stiffeners and the stitching in the skin panel area. The preform is completed, as shown in Figure 5, by stitching the bias 2D details to the main core piece.

The completed preform will have a 120-180% bulk, or 1.2 to 1.8 times the drawing net final thickness. Debulking will be done to compress the preform using a combination of stitching and a low-temperature melting point uncatalyzed epoxy resin binder.

Techniweave is currently in the process of installing a machine to automate the 3D weaving process and is scheduled to be on-line in the summer of 1992. The Grumman Window Belt subcomponent will be one of the initial products.

The translation of the original design into a preform required some compromise in fiber volume, stacking and percentage of fiber orientations. Table 1 shows the initial target fiber orientation percentages from the engineering drawing and the resulting preform compromise from Techniweave. Techniweave will use AS4 - 3K yarn for the stiffener 0-degree orientations and panel 0, 90, ± 45-degree orientations. The "Z" direction weaver yarns will be T300-1K. The stiffener 90-degree orientation and all stitching will be achieved using Toray T900 high-strength graphite yarn. The 2D material will be AS4-5H. The basic design concept for the stiffeners is shown in Figures 10, 11 and 12.

There are several unique aspects of this process that are beneficial to fabricating preforms. Among these are the ability to weave the preform in the draining orientation without requiring an unfolding operation, the ability to weave the skin and intersecting stiffeners as one core detail, the potential for automation and scale-up, and the ability of weaving in-plane holes into the preform.

ICI Fiberite Process

The ICI Fiberite approach to the window belt design is conceptually shown in the schematic of the test element in Figure 13. It consists of a 3D woven core and several 2D woven details that are assembled and debulked to form the preform. The core is produced on an ICI built loom capable of weaving thicknesses up to 3.5 in. and outfitted with a Staubli electronic Jacquard head.

The 3D core is the principal feature of the design and provides the through-the-intersection fiber continuity. Figure 14 shows the woven preform prior to being expanded and erected vertically. Essentially, it resembles a collapsed egg crate. The preform exits the loom in the longitudinal direction parallel to the 0-degree fiber orientation direction.

A schematic representation of the 3D fiber architecture is shown in Figure 15. The preform consists of three principal fiber orientations: 0-degree, which are depicted by the solid horizontal lines; "Z" direction, which are represented by the angular translational lines; and the 90 degree fill yarns shown by the circles. The through-the-intersection fiber continuity is shown and is achieved by rotating the 0.17 in. thick stiffener legs 90 degrees.

Producing this preform is a compromise of the initial target drawing fiber volumes and percentages, as shown in Table 1. For this process, "Z" yarns are introduced and are required to interlock the longitudinal and fill yarns together, thus giving a structural rigidity to the preform. These "Z" yarns replace some of the longitudinal 0-degree, as they do in the Techniweave process. The angular paths are expected to reduce the stiffener axial load capability. This will be verified during the testing phase. Also, the angular path of the "Z" yarns is related to the thickness of the assembly. The longitudinal stiffener (0.24 in. thick) angle is 44 degrees and the vertical stiffener (0.17 in. thick) angle is 20 degrees. The severity of the angle is expected to be directly related to the stiffness and axial load capability.

The 2D broadgood material that makes up the remainder of the preform definition is assembled to the 3D core to form the skin panel, stiffener buildups, and flanges. For this application these plies take the form of strips, sheets, and pans. Figures 16 and 17 show the completed preform cross-sectional assembly of the longitudinal and vertical stiffeners. Figure 18 shows the plan view of the assembled stiffener intersection.

ICI debulks the complete preform to as close to net shape as possible using a tackifier or binder resin. An uncatalyzed epoxy resin, 8% volume, is sprayed on the woven details prior to the preform assembly to provide a tackiness to hold the net dimensional compressed shape and to add rigidity to the preform. This tackifier is a Shell product, a combination of Epon 836 and 1001F, and has a low melting point of 130 deg F. This compressed preform is stitched using a Kevlar thread at a 1/4 in. stitch pitch in 3/8 in. spaced rows. The stitching provides additional rigidity to the preform and aids in holding the net dimensional shape. Stitching is a requirement to enhance the damage tolerances of the assembled 2D material. For this application the stitching volume percent is less than 2.

A 14 in. x 14 in. cross-stiffened preform test element fabricated by ICI is shown in Figure 19. This cross-stiffened element represents a stiffener intersection of the window belt and was used to demonstrate the preform fabrication methodology. Similar test elements will be used during subsequent tests to demonstrate RTM and RFI processibility and structural performance.

This preform will utilize IM7 graphite for the preform yarn and 2D woven broadgoods as the basic construction material. The 3D core woven detail will be fabricated using 12K yarn for the 0°, 90°, and "Z" angular directions.

TOOL DESIGN

The tooling concept employed for the RTM process will be a bolted multi-piece steel mold that provides a compression/wedge action. An assembly of the subcomponent tool is shown in Figure 20. Although a press is preferred for tool closure, a bolted strong back design was selected due to the size limitations of the current prototype RTM lab facility press, 30 in. x 30 in. The wedge action provides the side pressure on the preform as the mating tool is closed to complete the debulking to the final part dimensions and to attain the required fiber volume. Inserts within the tool are free and permitted to float.

Other tooling concepts considered include aluminum mandrels/steel base plate, an aluminum-filled epoxy casting system, and rubber intensifiers. These concepts were discarded in favor of the steel wedge design based on positive past experience.

The injection design will be multi-port, one at each center support post, with four vent exits. Also included in the design is a resin reservoir on the two long sides which provides resin reserve to back-fill the preform during cooling.

Resin flow will be initially determined by using a broadgoods replica preform in the tooling prove-out phase. The tool will be evacuated and the resin introduced at 50 psi and 180°F. Upon resin introduction, the exit ports will be opened and flow regulated to ensure complete filling. Sequencing and utilization of the exit ports will be determined. This trial method will provide confidence in the process prior to curing the graphite preform.

TESTING

The cured 30-in. x 62-in. window belt subcomponent and 7-in. x 7-in. element preform assemblies will be tested as shown in the test matrix, Figure 21. These tests will evaluate the tension, compression, shear and normal tension, and related elastic properties of the two textile preform supplier's test articles. The small elements are representative of the cross-stiffened intersections. Results from the finite-element analysis will be used to predict failure and the high-strain areas to locate the strain gages.

All testing will be accomplished at the Grumman Elements and Material Test facility. An MTS servo-hydraulic 'mega' machine, 1,000,000 lb calibrated capacity, will be used to test the subcomponent and a MTS servo-hydraulic, 90,000 lb, machine will be applied to the smaller test elements.

DESIGN CONCERNS

Designers who employ textile preform technology for airframe structures need a significant insight into the processing methodology to adequately define the part, design the tooling, and be confident in the end product performance. Based on the two preform methods presented in this paper, there is a significant difference in approach and final end product. The difference in material, tow and yarn sizes, weaving architecture, utilization of binders (tackifiers), stitching, and bulk will interact and is expected to result in different end product performance. There is much that must be developed further, and standardized, or at least controlled, to ensure repeatability and structural integrity from one textile supplier to another.

The engineering drawing presentation utilizing percentages of fiber orientations provided freedom to define the preform but resulted in diverse approaches that will have an impact on the end product performance. Drawing improvements and standards must be defined that will more capably control the end result. There is much to be learned in providing engineering definition to woven preform assemblies. As it stands now, this type of design freedom would not be permitted for production hardware since geometry and structural integrity are essential for product performance.

The test base for recurring weaving architectural patterns must be expanded in order to assess the impact on structural properties. The knockdowns associated with the 'Z' weaver locking yarns and stitching must be determined.

The analytical methodologies must be further developed to be able to predict structural capability considering the variation of architecture, varying yarn size, fiber volume, and defects.

The application of the uncatalyzed epoxy binders and tackifiers which are used to enable debulking of the preform must be thoroughly evaluated to assure that there is no deleterious effect on the processed article. These assessments should consider the effects of percentage of resin content, effects of nonuniform mixture with the structural resin, necessity to purge, and compatibility with both RFI and RTM processing methods.

The preform net final dimensions must be closely controlled to enable effective tooling to be designed. Bulk factors of 100 - 200% are unacceptable for pocketed cross-stiffened preforms. It would be desirable to provide debulked preforms to 10% of net.

CONCLUSIONS

The final assessment is that through-the-intersection continuous fiber cross-stiffened woven preform assemblies that offer a scale-up potential are feasible. This potential offers unique composite material solutions to all cross-stiffened applications such as bulkheads, frames, keels, beams, skin panels, and doors. The focus should be expanded to develop a solid data base and preform definition.

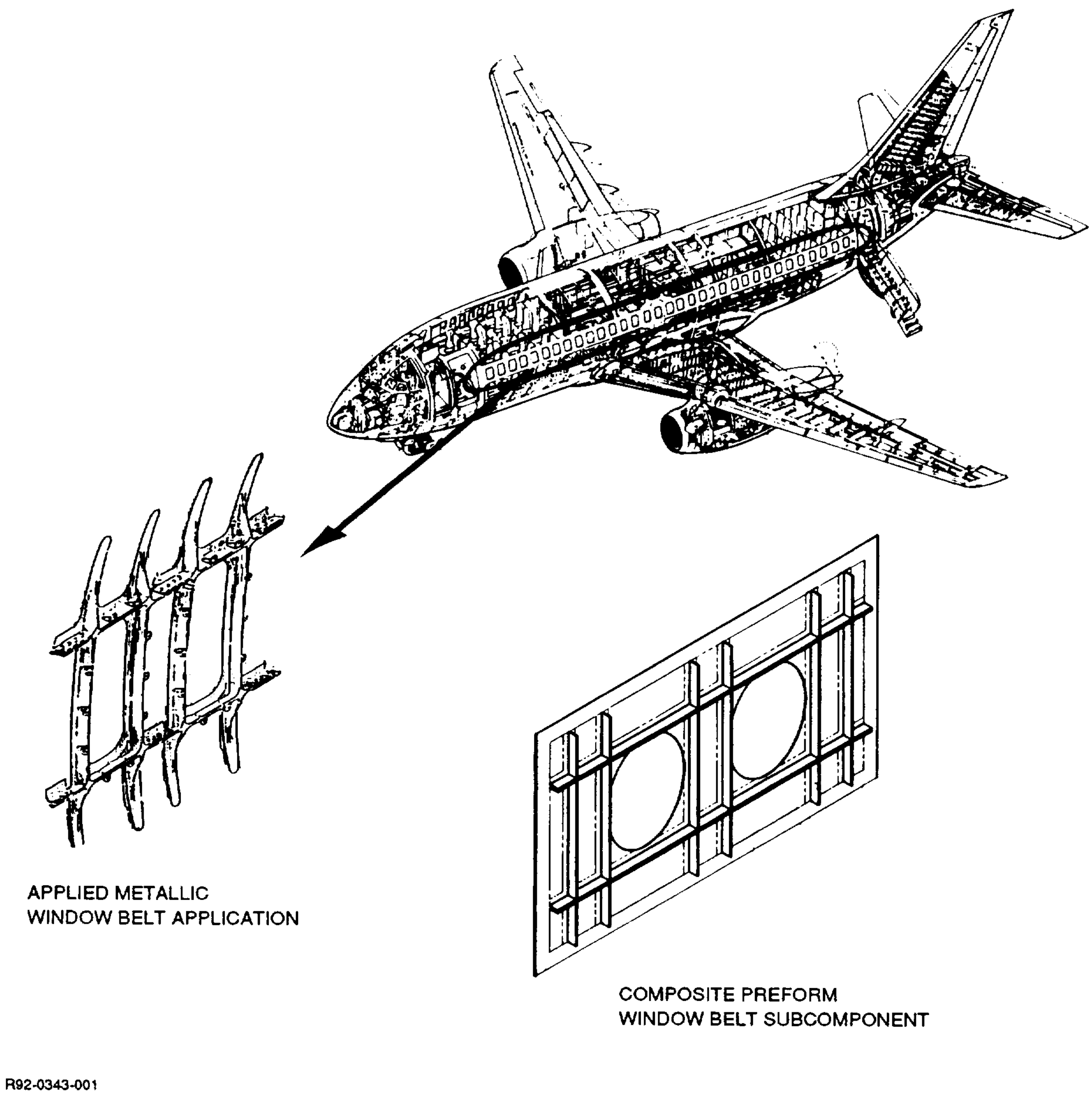
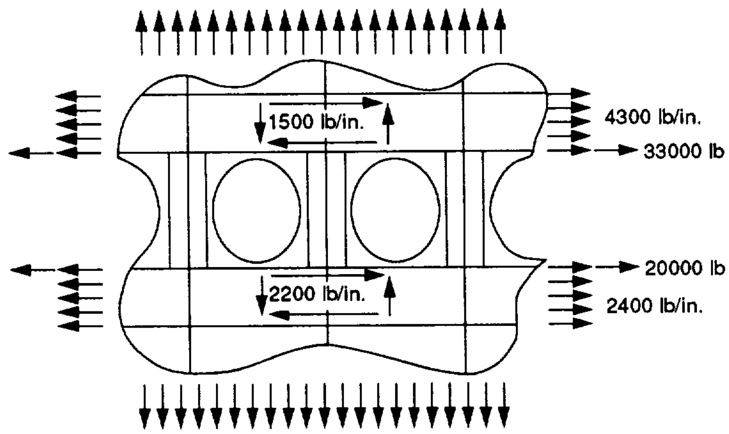
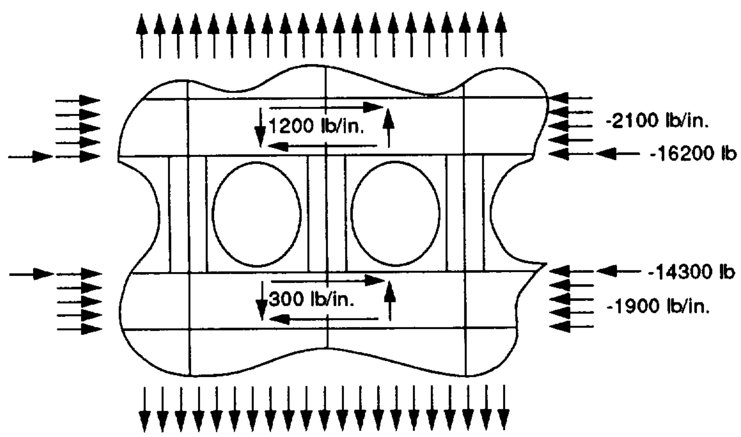


Figure 1. Cross stiffened structure airframe application.



A. MAXIMUM TENSION AND SHEAR STA 1424



B. MAXIMUM COMPRESSION AND SHEAR STA 1424

MR92-0343-002

Figure 2. Window belt maximum load conditions.

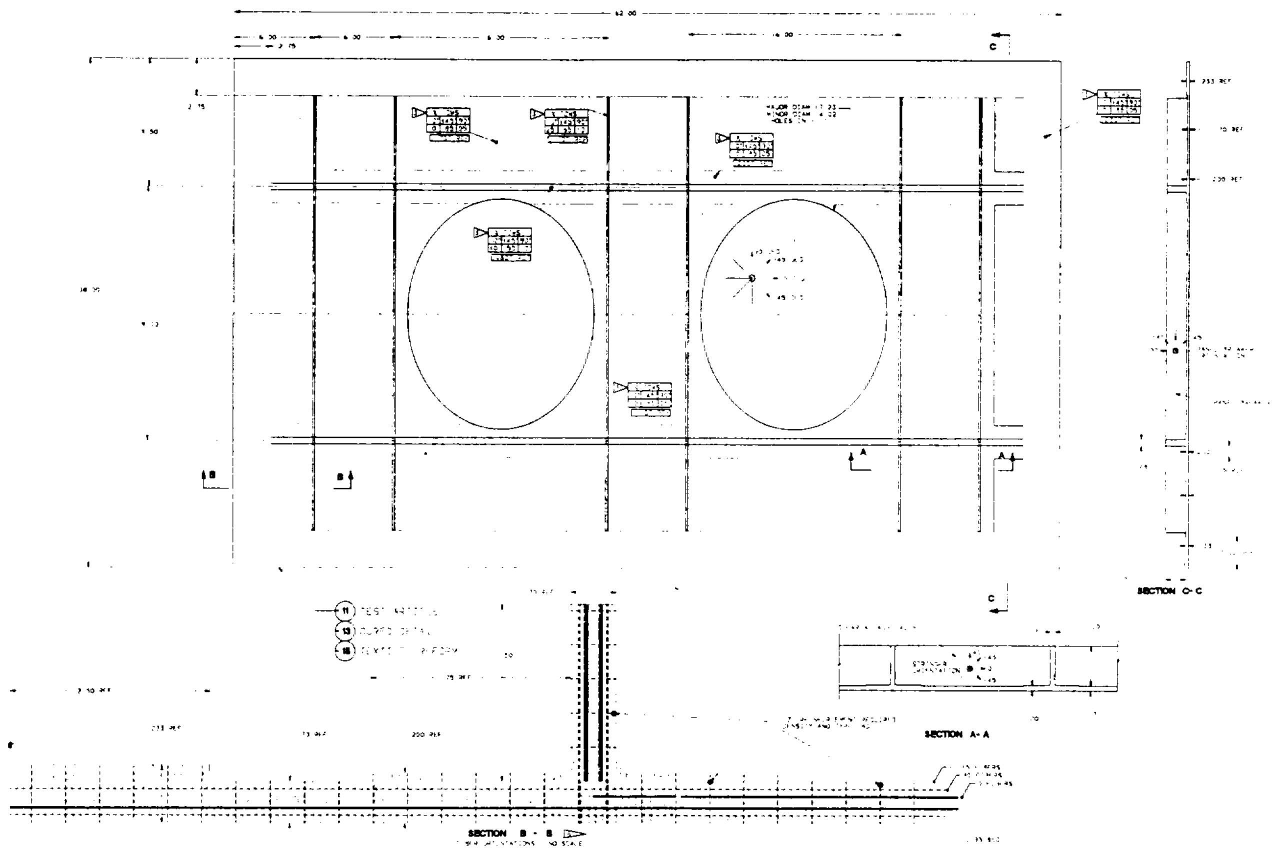


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Figure 3. Cross-stiffened 3D woven window belt design, Dwg D19B1865.

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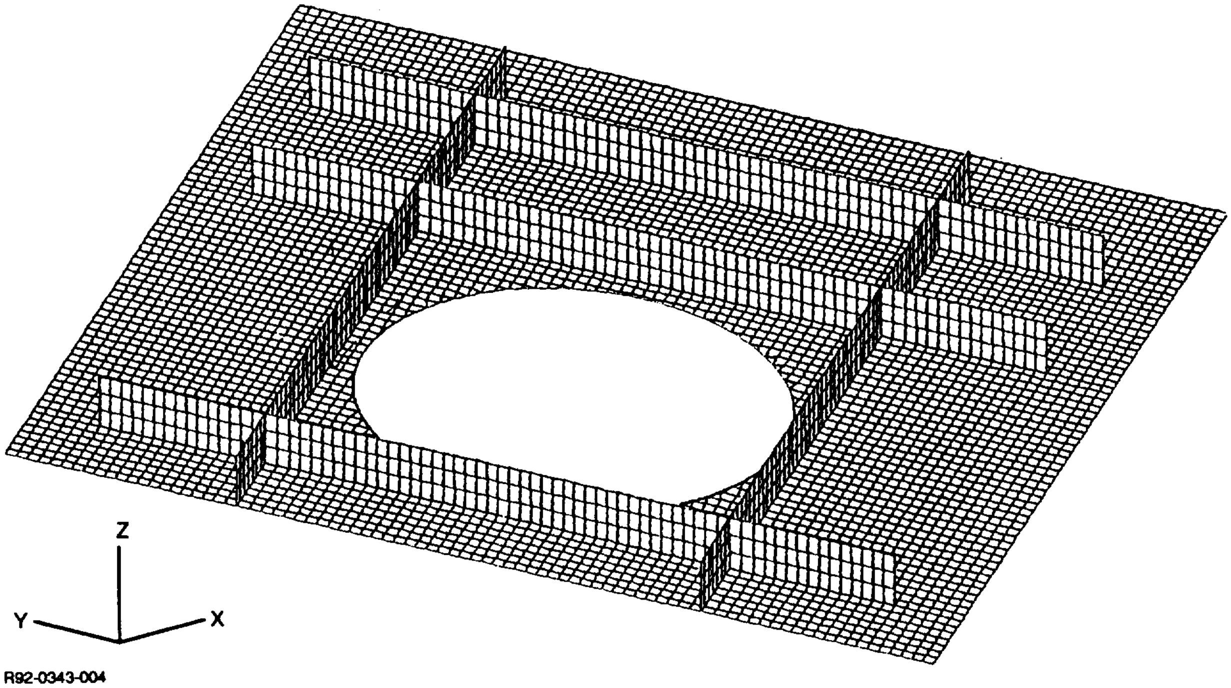

Figure 4. Finite element model, repeating section of window belt.

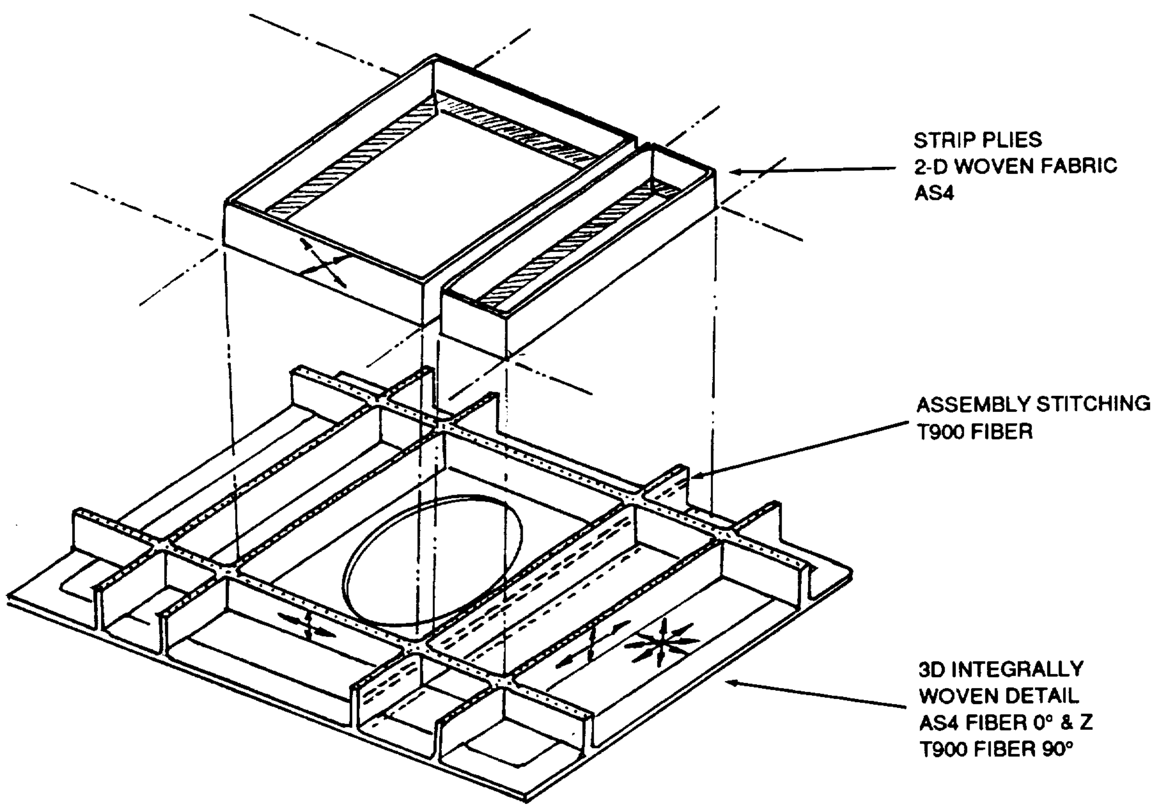

Figure 5. Preform assembly Techniweave, Inc. method.

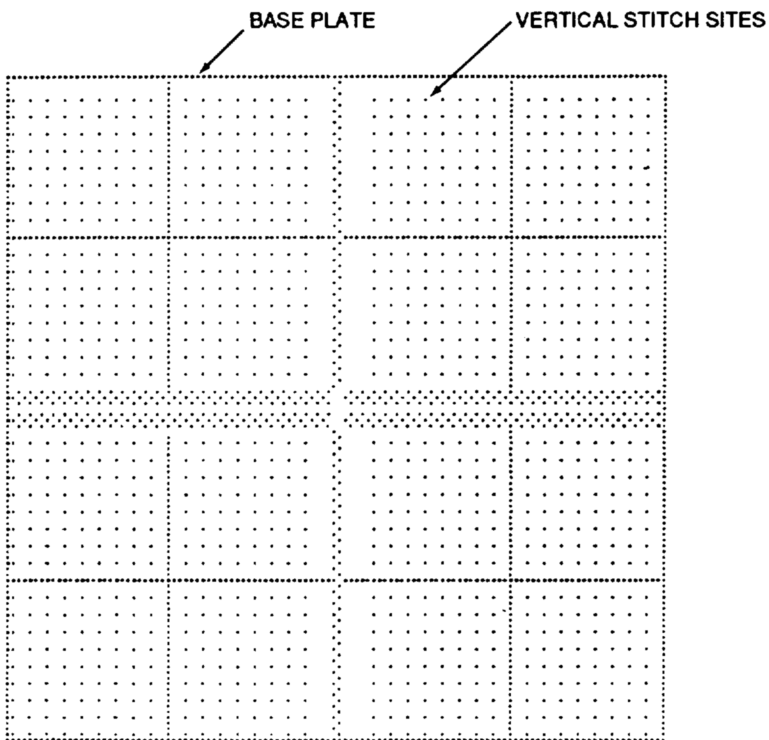

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Figure 6. 7 x 7 test element pin pattern.

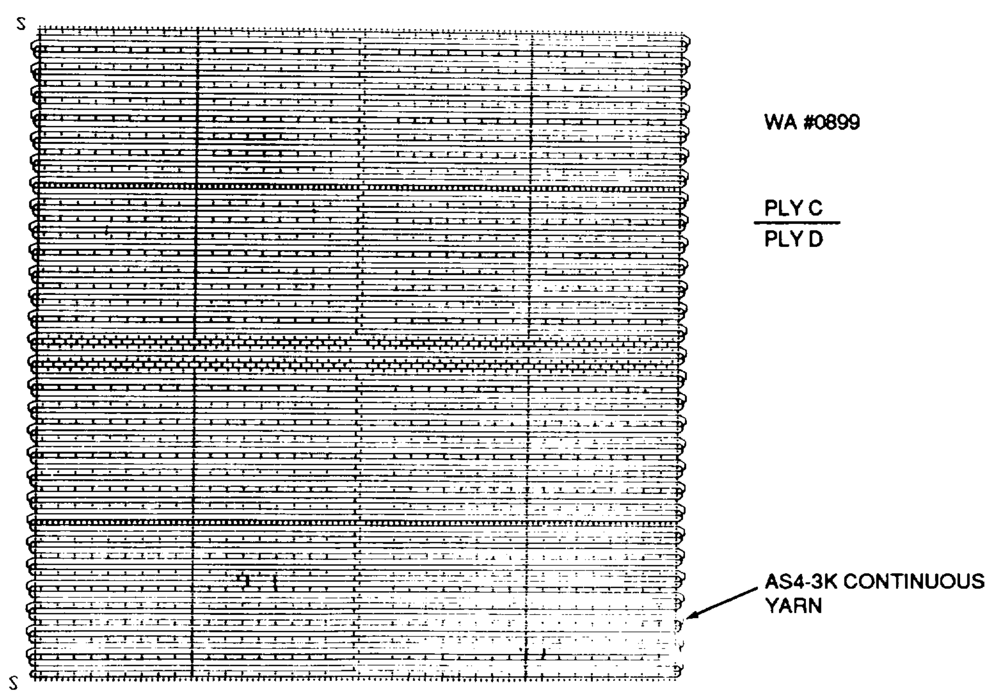

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Figure 7. 7 x 7 test element skin panel, 0° layers.

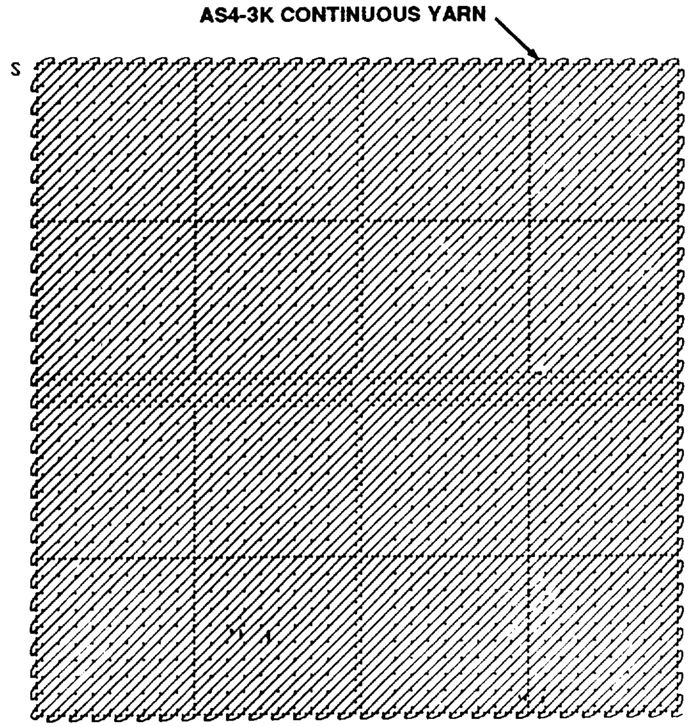

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Figure 8. 7 x 7 test element skin panel, 45° bias layers.

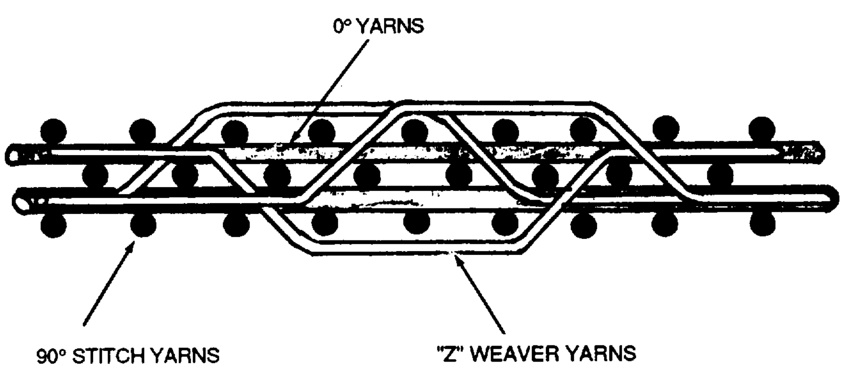

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Figure 9. Weaving pattern - Techniweave.

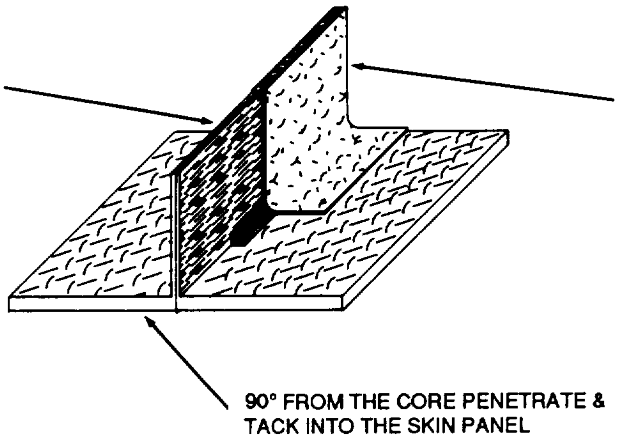

Figure 10. 0.17 stiffener construction.

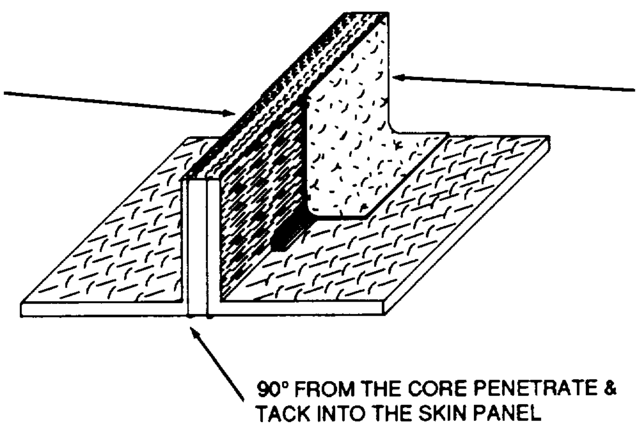

Figure 11. 0.48 stiffener construction.

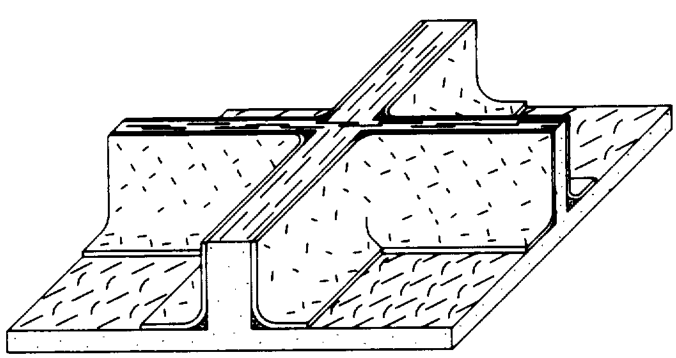

Figure 12. Typical rib intersection.

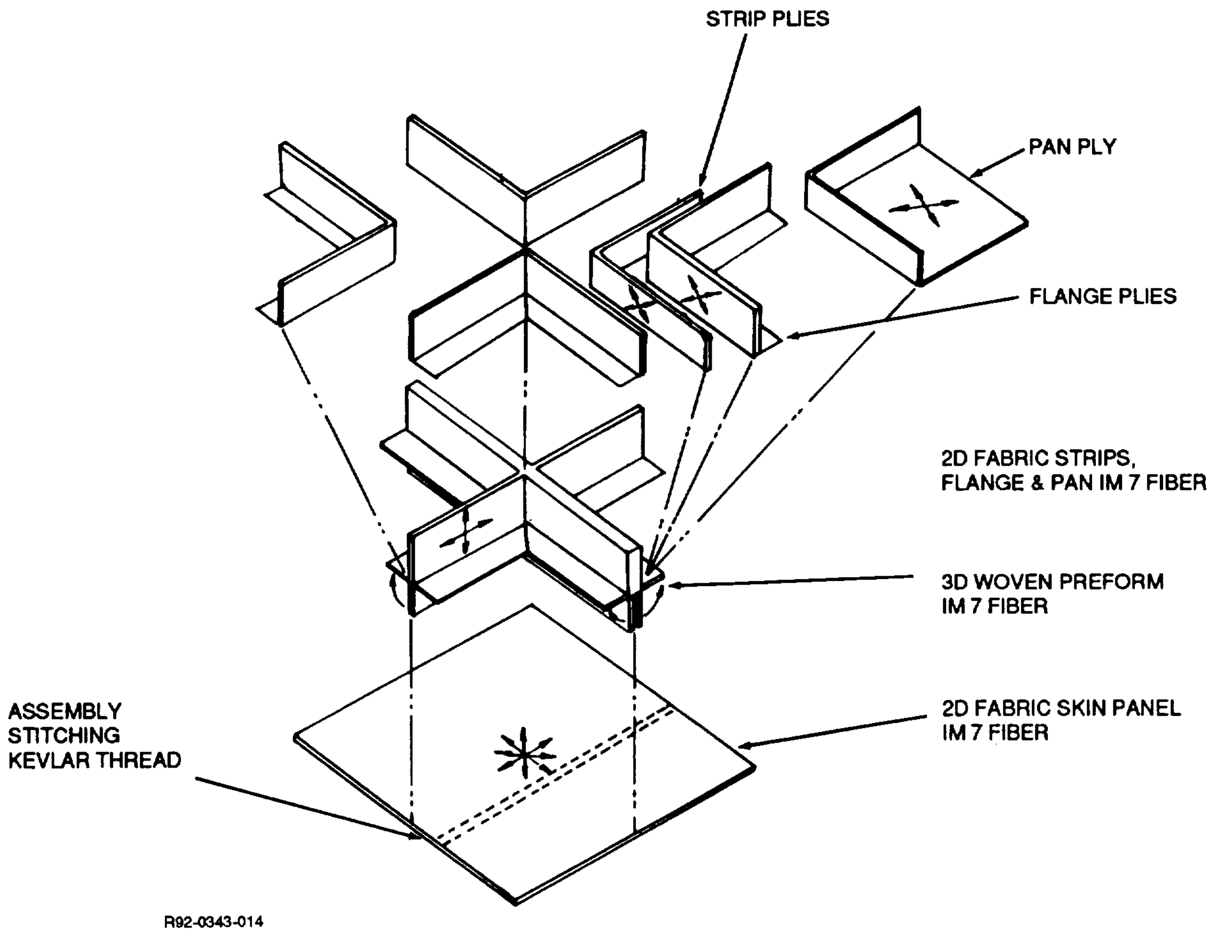

Figure 13. Test element preform assembly, ICI method.

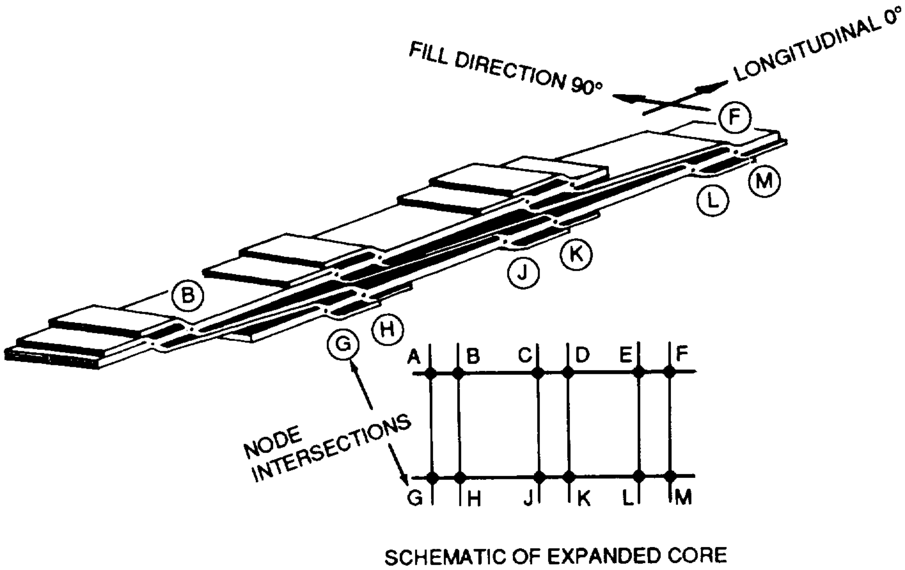

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Figure 14. Unexpanded as-woven, core detail by ICI Fiberite.

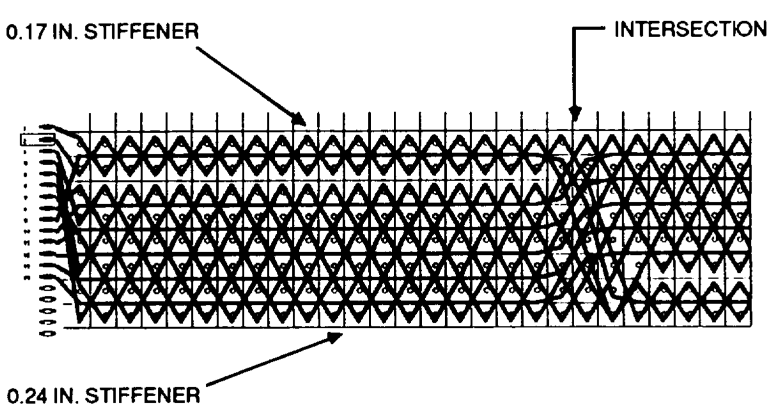

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Figure 15. Fiber architecture 3D woven core perform, ICI method.

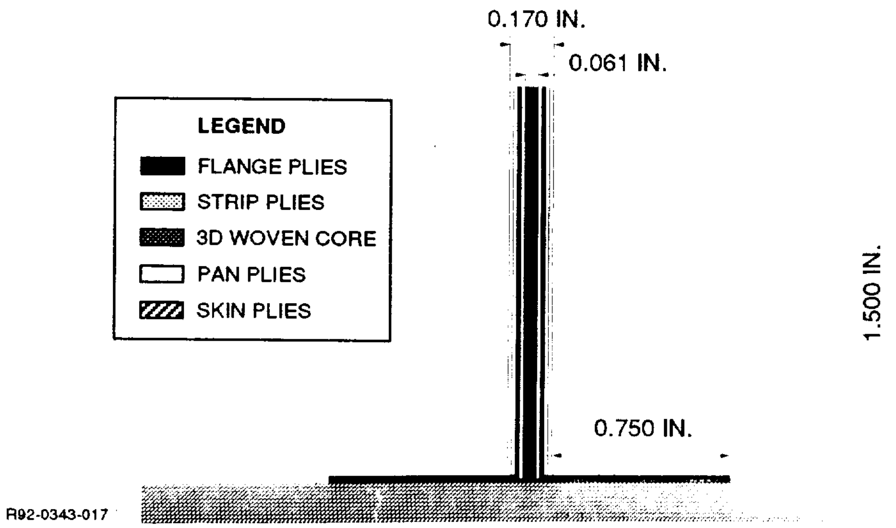

Figure 16. 0.17 In. thick stiffener – ply layup, ICI.

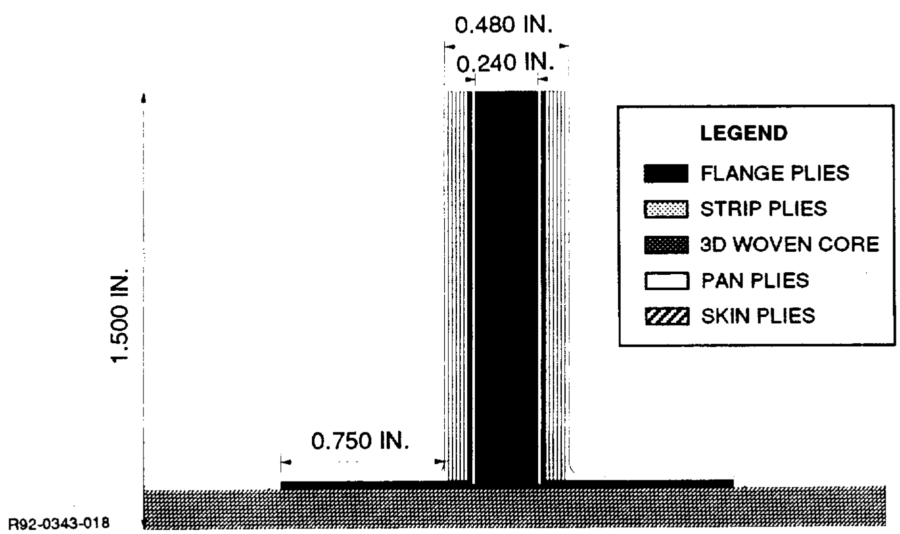

Figure 17. 0.48 In. thick stiffener – ply layup, ICI.

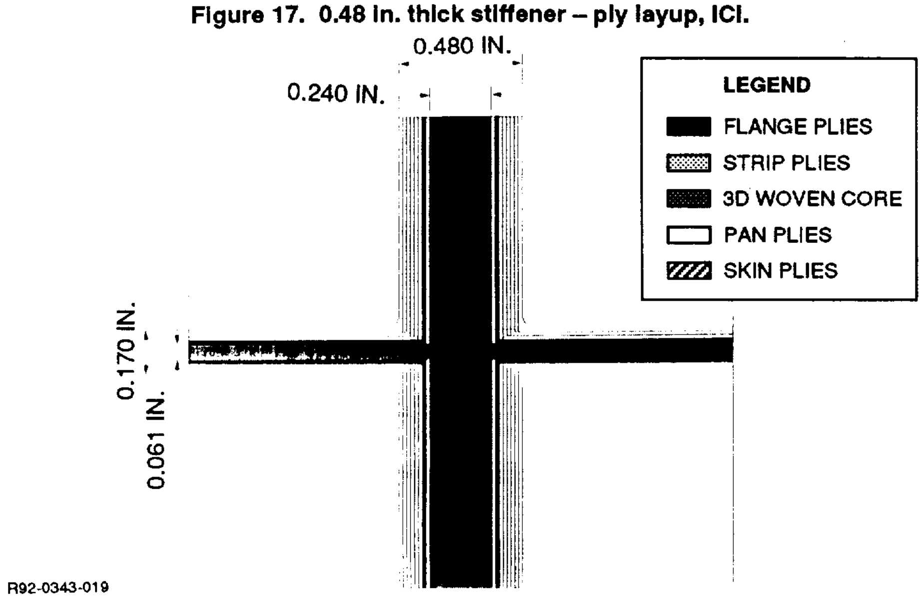

Figure 18. Intersection — ply layup, ICI.

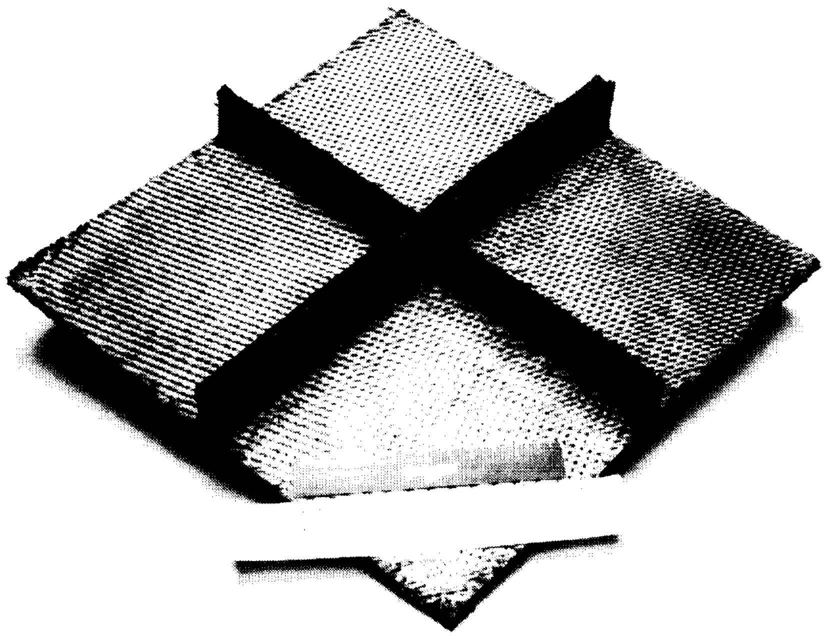

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Figure 19. 14 in. x 14 in. woven cross-stiffened test element, ICI Fiberite .

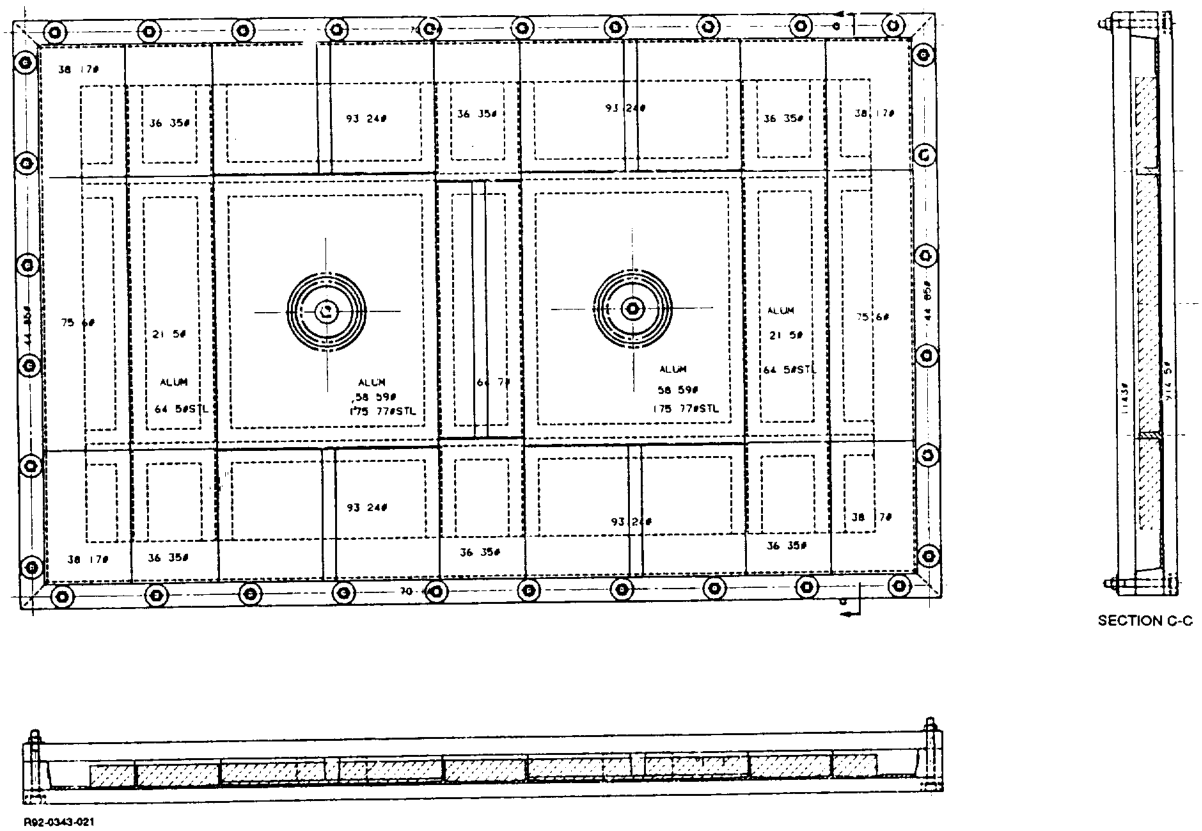
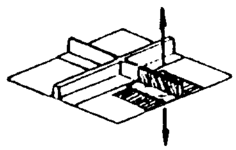
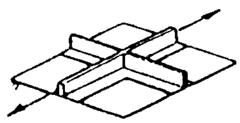
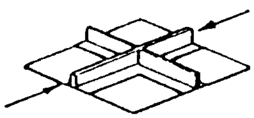
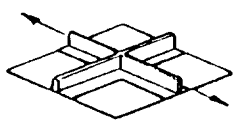
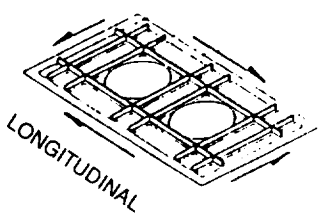


Figure 20. Tooling design concept, window belt subcomponent drawing D19B1865-11BOF .

SPECIMEN	TEST	DESCRIPTION
	ELEMENT NORMAL TENSION AMBIENT COND	1.5 x 1.5 3 ARTICLES, TECHNIWEAVE 3 ARTICLES, ICI FIBERITE
	ELEMENT AXIAL TENSION LONGITUDINAL AMBIENT COND	7.0 x 7.0 2 ARTICLES, TECHNIWEAVE 2 ARTICLES, ICI FIBERITE
	ELEMENT AXIAL COMPRESSION LONGITUDINAL AMBIENT COND	7.0 x 7.0 1 ARTICLES, TECHNIWEAVE 1 ARTICLES, ICI FIBERITE
	ELEMENT AXIAL TENSION CIRCUMFERENTIAL AMBIENT	7.0 x 7.0 1 ARTICLES, TECHNIWEAVE 1 ARTICLES, ICI FIBERITE
	SUBCOMPONENT SHEAR AMBIENT COND	38.0 x 62.0 1 ARTICLES, TECHNIWEAVE 1 ARTICLES, ICI FIBERITE

R92-0343-022

Figure 21. Test matrix, cross-stiffened structure.

Table 1. Preform Fiber Orientation Percentages, Fiber Volume and Material.

APPLICATION & ORIENTATION	GRUMMAN D19B1865 TARGET VALUES	TECHNIWEAVE METHOD	ICI FIBERITE METHOD
PANEL			
0 DEG	10%	12% AS4-3K	9%
±45 DEG	85%	82% AS4-3K	82%
90 DEG	5%	6% AS4-3K	9%
Z	NA	N/A	NA
FIBER VOLUME	58%	57%	58%
HORIZONTAL STIFFENER			
0 DEG	40%	38% AS4-3K	28% IM7-12K
Z	NA	3% T300-1K	8% IM7-12K
±45 DEG	50%	46% AS4-5H	54% IM7-5H
90 DEG	10%	10% T900-3K	10% IM7-12K
FIBER VOLUME	58%	57%	52%
VERTICAL STIFFENER			
0 DEG	25%	28% AS4-3K	15% IM7-12K
Z	NA	6% T300-1K	5% IM7-12K
±45 DEG	65%	56% AS4-54	72% IM7-5H
90 DEG	10%	9% T900-3K	8% IM7-12K
FIBER VOLUME	58%	54%	56%
ASSEMBLY			
STITCHING	LESS THAN 6%	2% T900-3K	2% KEVLAR

R92-0343-010