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Cost-Efficient Manufacturing of Composite Structures

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Abstract

The Advanced Composites Technology (ACT) program is seeking research breakthroughs that will allow structures made of graphite epoxy composite materials to replace metal in the wings and fuselages of future aircraft. NASA's goals are to reduce acquisition cost by 20-25 percent, structural weight for a resized aircraft by 40-50 percent, and the number of parts by half compared to current production aluminum aircraft. This presentation will focus on the innovative structural concepts, materials, and fabrication techniques emerging from the ACT program, and will discuss the relationship between aerospace developments and industrial, commercial, and sporting goods applications.

Introduction

Boeing Commercial Airplane (BCA) Group and Douglas Aircraft Corporation (DAC) use approximately 400,000 pounds of composites per year in spoilers, rudders, elevators, doors, and other secondary structure. The rate of application of composites to empennage, wing, and fuselage commercial airframe primary structure has been disappointingly slow. Composite materials are an obvious choice for performance optimization, corrosion resistance, and fatigue suppression but before a bold leap toward more extensive use of composites can be expected in commercial applications, lower acquisition costs and confidence that production costs can be accurately predicted must be demonstrated. The Advanced Composite Technology Program's goal is to establish the design concepts, develop manufacturing approaches, and demonstrate mechanics and cost performance of innovative low cost composite assemblies providing confidence for production commitment to primary structure by the turn of the century.

State-of-the-Art

The application of composite structures to commercial transport aircraft is proving to be an evolutionary process. The National Aeronautics and Space Administration (NASA) has sponsored the development, certification and flight service evaluation of composite secondary and empennage structure for components shown in Table 1 (1). Secondary and empennage composite structures are in production on

	Secondary			Empennage		
Component	DC-10 rudder	727 elevator	L-1011 aileron	DC-10 vertical stabilizer	737 horizontal stabilizer	L-1011 vertical fin
Size (root X span), ft.	3.2 X 13.2	3.4 X 17.4	4.3 X 7.7	6.8 X 22.8	4.3 X 16.7	8.9 X 25
Metal design weight, lb.	91	130	140	1,005	262	858
Composite design weight, lb.	67	98	107	834	204	622
Weight reduction, %	26	25	24	17	22	28
Number of production units	20	11	12	3	11	2
Start flight service	4/76	3/80	3/82	1/87	3/84	-

Table 1. - Composite structures developed under NASA ACEE program.

several transport aircraft. The weight reduction potential of composite structures is well documented in an excellent bibliography with over 600 references on NASA sponsored composites research between 1976 and 1986 that was published in 1987 (2). Boeing 737 spoilers for the NASA flight service program have been in service since 1973 and after 15 years of flight service indicate no loss in residual strength (3).

Flight service experience made possible the production commitment of secondary composite structures on the Boeing 767 shown in Figure 1. Full exploitation of the benefits of composites requires application to wing and fuselage structures which account for 75 percent of the aircraft structural weight. The cost to develop and produce composite structures remains the major barrier to increased application of this technology to transport aircraft, shipbuilding and general industrial use.

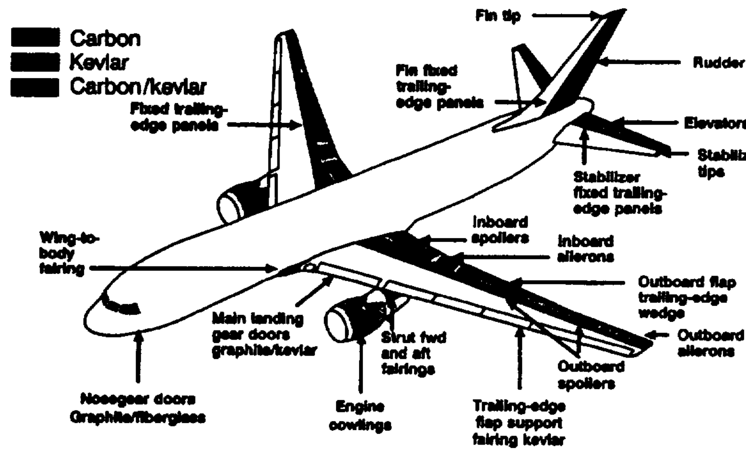


Figure 1. - Current Boeing Commercial Airplanes composite usage.

The ACT program

In 1984 NASA requested that the Aeronautics and Space Engineering Board of the National Research Council (NRC) form a committee to assess the status and viability of organic matrix composites technology for aircraft structures. The committee findings and recommendations were reported in 1987 (4) and recommended that NASA establish a program to develop an integrated "affordable" composites technology database to reduce the risks of employing new cost effective designs and fabrication processes. In 1988 NASA initiated the ACT program with emphasis on development of advanced materials, mechanics, innovative concepts, and low cost manufacturing methods. This paper will provide detail on the improved material forms, tailored cost effective design concepts, and innovative low cost manufacturing methods that are under development and expected to lead to an "integrated database" of affordable composite concepts. The term "integrated database" relates to materials and structural issues required to reduce the risks of applying new composite designs to large structure production applications. Data to be developed include materials properties, test methods, analytical methods for predicting structural response and strength, manufacturing and inspection methods.

Until the database for the composite structures reaches a level of maturity comparable to that for current metallic structures, fabrication and testing of full-scale components will be required to demonstrate performance and cost goals. Before the commitment to develop and build a composite primary airframe is made, full-scale fabrication and tests of a wing box, a fuselage barrel and possible the wing-fuselage attachment will be required to demonstrate that an "affordable" database exists. Technology verification for the next decade is expected to require fabrication and testing of full-scale wing-box and fuselage-section components before certification can occur and production commitments can be made.

Potential Benefits

Composites structures are recognized as enabling technology for making significant advances in the performance of subsonic transports and are essential to achieving an economically viable supersonic transport. Prior research and development programs have demonstrated weight savings greater than 25 percent and, when the effects of improved damage tolerant materials and resizing the aircraft are taken into account, the weight savings for some components may approach 40 percent. Composite structures that have been designed as replacements for metallic structures contain significantly fewer parts and numerous studies have noted the direct relation between part count and cost. Cost estimates that range from 10 to 40 percent less than metallic structure have been reported for the projected acquisition cost for composite structure in future production (5). The weight savings of composite structure translates into about 10 to 15 percent fuel savings (6). Outstanding resistance to environmental degradation and residual strength after exposure to cyclic fatigue loading offer the potential for building aircraft with longer life and reduced maintenance cost (7). Recent studies indicate that composite structures are essential for design of an economically-viable 5000-nautical-mile-range supersonic aircraft (8). Composites are required to hold the gross takeoff weight to less than 750,000 pounds and allow landing on existing runways.

The recent emphasis on reducing composite structure acquisition cost to less than equivalent metallic structure cost will provide a broad range of opportunities for application of high performance composite materials in shipbuilding and heavy industry with renewed opportunities in the automotive, commercial, and sporting business sectors. Order of magnitude increases in volume requirements for composites can be envisioned in the next 2 decades as commercial airplane wing and fuselage and large shipbuilding applications evolve, resulting in additional decreases in raw material cost. New indefinite room temperature storage composite material textile forms are expected to make warehousing of structural building blocks possible and high modulus graphite composites routinely available to the home hobbyist and building construction markets.

Design/Manufacturing Engineering

The preliminary design phase has been identified as the most opportune period during an airframers hardware production cycle for substantial cost reduction. Boeing has experienced that 70% of airplane fabrication costs are fixed by the time the design is frozen and that the influence of engineering on fabrication cost reductions is significantly reduced once the design is completed. Concurrent engineering interdisciplinary teams are emphasizing cost evaluation at the early stages of the development cycle. Perhaps, the most important approach for achieving an affordable composites data base is through the integration of design and manufacturing disciplines. The Design/Manufacturing Integration (D/MI) approach brings together all disciplines (see Fig. 2) that have an influence on the performance and cost requirements

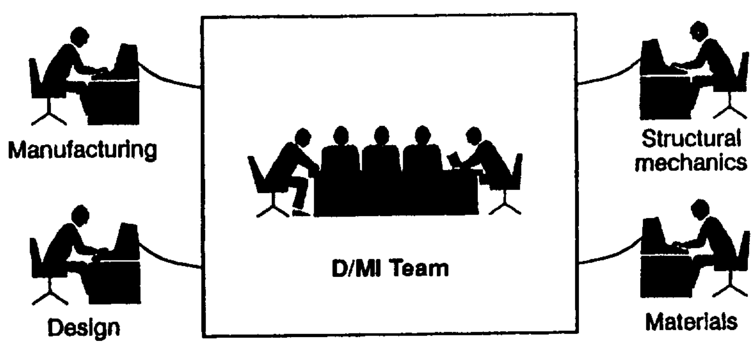


Figure 2. - Design/manufacturing integration (D/MI) program.

at the beginning of the design process. Figure 3 provides a schematic of the results of the DM/I process for a simple stiffened skin compression panel. The influence of design concept on cost and weight is the product of the D/MI process. The interaction of interdisciplinary teams can perform trade studies quickly resulting in less changes as the design is completed. Airframe companies have begun to practice the D/MI approach and large benefits from this approach will appear in the next generation of aircraft.

Rapid advancements in computer hardware and software capability at continually reduced cost has made computer aided design and manufacturing (CAD/CAM) practical for storing complete 3-D electronic product definitions of complex composite structures. These concepts proven on the B-2 program "minimize costly and time consuming toolmaking phases" normally associated with development of composite structures (9). Companies employing computers to rapidly manipulate 3-D hardware definition databases will develop D/MI capabilities that allow the designer to optimize composite material properties while tailoring the performance and cost of the structure. One ACT program goal is to develop a designers cost model that will be integrated with a structures optimization model to trade cost and weight during the conceptual and preliminary design phases.

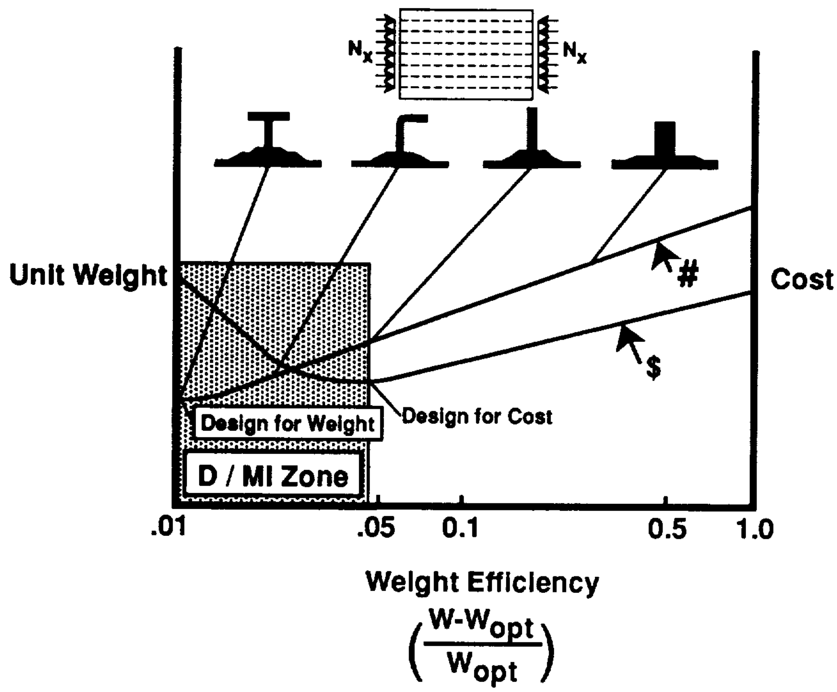


Figure 3. - Influence of design/manufacturing integration.

Design Concepts

Composite structures for aircraft applications have historically been designed using standard metallic stiffened-skin design practices. Composite design concepts are now being developed to reduce both weight and cost. Design concepts that reduce fabrication and assembly costs can often be cost-effective even with more expensive materials. Boeing is studying pressurized fuselage concepts for the ACT program using design concepts that result in lower cost structures by reducing the number of parts and associated fasteners that have to be assembled. Figure 4 shows a concept to build large one piece composite panels reducing the total number of panels for a 757 class airframe to 19 panels. The equivalent

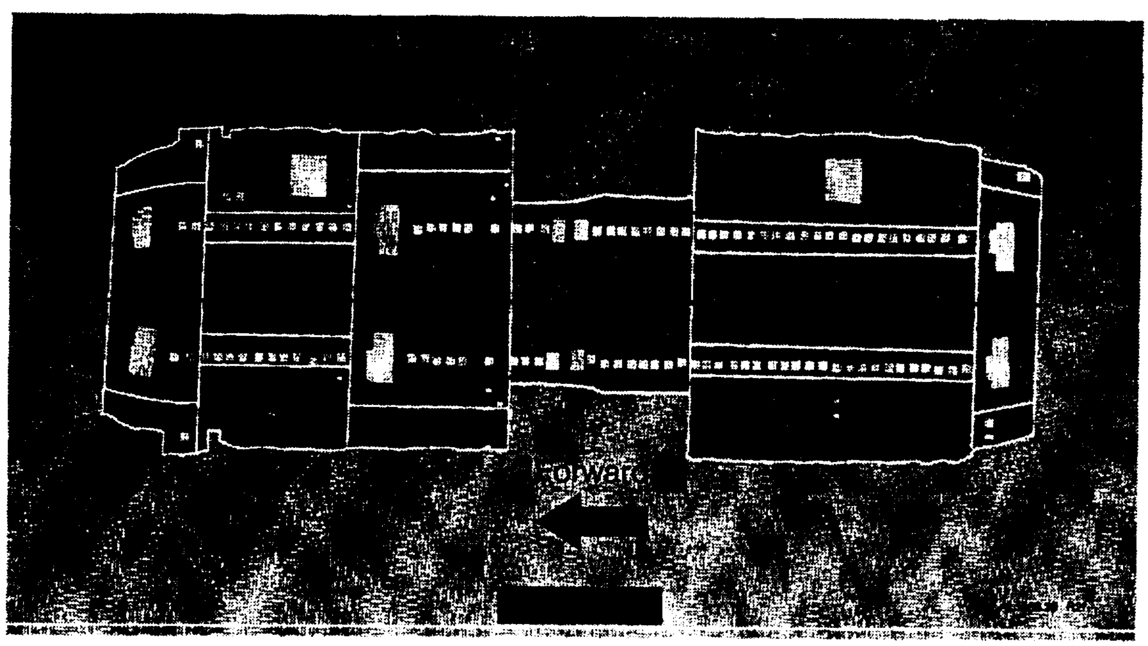


Figure 4. - Design concepts

metallic structure has 72 panels due to limits on sheet metal width availability. Several structural elements can be integrated into the composite structure during subcomponent fabrication by cocuring the stiffeners with the skin to significantly reduce the number of fasteners, clips and shear ties needed to assemble conventional metallic stiffened structures. Sandwich structures are being considered to minimize or even eliminate the need for stiffeners. Figure 5 shows concepts for composite fuselage quadrant panels designed

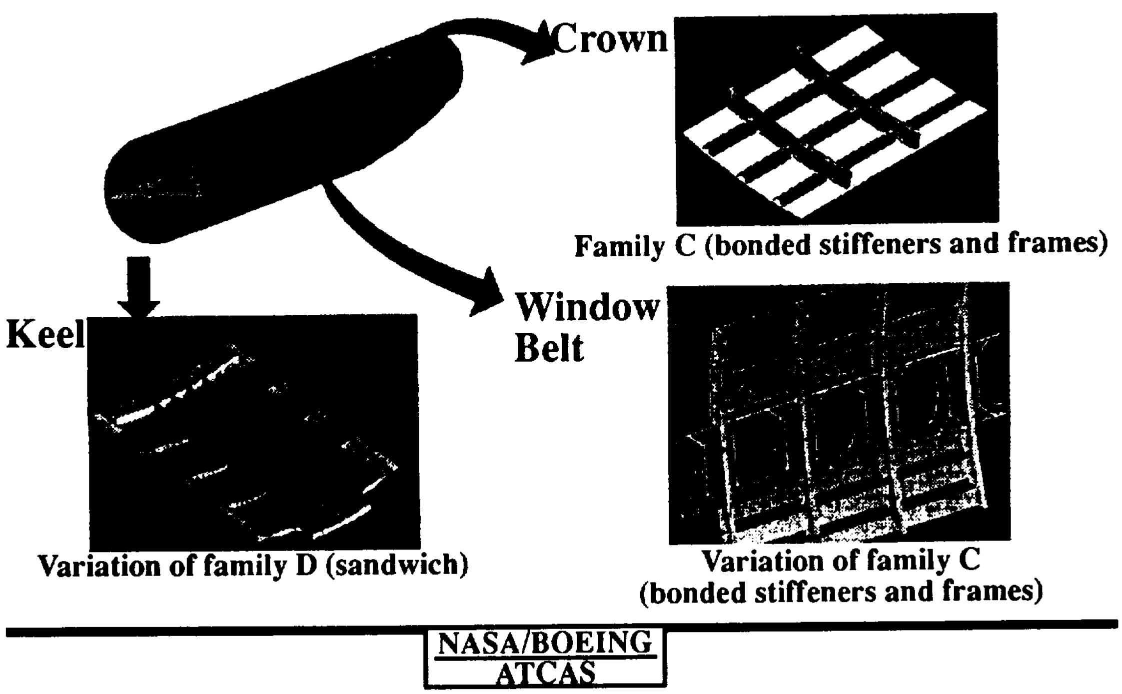


Figure 5. - Baseline fuselage concepts.

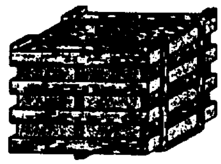
for an all composite aircraft rather than a conventional metallic replacement. Large one piece composite panels (up to 32' by 20') can eliminate dozens of complex joints and countless thousands of fasteners that are common to metallic assemblies. Boeing estimates as much as a 51% weight savings with acquisition costs equal to equivalent metallic structure for composites built by these concepts, even with today's high cost materials. Their confidence that large one piece structures can be fabricated comes from experience noted in an Aviation Week article, "Boeing's B-2 facility Produces Largest Composite Structural Parts Ever Made" (10).

Materials and Material Forms

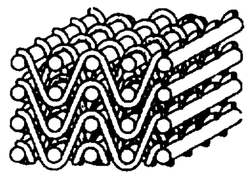
To successfully replace state-of-the-art (SOTA) metallic materials, carbon fiber reinforced polymer composites must exhibit a favorable balance between toughness, damage tolerance, processibility, and cost. The primary resin matrix for subsonic aircraft structure in service today is a brittle 350°F curing epoxy system that does not exhibit the toughness and damage tolerance required for heavily-loaded primary aircraft structure. Toughened matrix materials now cost at least three times that of the conventional brittle epoxy systems and are generally too expensive for widespread use on commercial aircraft (11).

Thermoplastic composites offer an attractive combination of mechanical properties, toughness, and the potential for low-cost manufacturing. They provide simple formulations, excellent prepreg stability, indefinite work-life, no requirement for cold storage, and rapid thermoformable processing. Solvent resistant thermoplastic tape is currently much more expensive than conventional brittle epoxy prepreg. ACT Program participants are developing and evaluating powder coated fiber, textile preform technology, and resin transfer molding (RTM) materials to reduce the materials cost associated with composites.

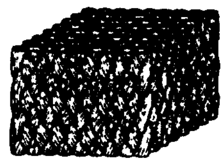
An exciting approach to low cost composites that exhibit exceptional toughness is the use of net-shaped textile fiber architecture preforms that can be infiltrated by RTM processes and cured in an oven or autoclave (12,13,14). Automated textile processes such as weaving, braiding, knitting and through-the-thickness stitching would provide highly automated processes for reduced material cost. Complex fiber architectures as shown in Figure 6, multilayer fabrics and structural composite preforms have been demon-



Stitched/woven fabric



Layer-to-layer interlock weave



3-D braid

Figure 6. - Through the thickness reinforced textile forms.

strated using automated textile technologies. These dry fiber preforms lend themselves to economical composite fabrication techniques including RTM and pultrusion. Stitched fabric preforms impregnated with low cost epoxy matrix resins exhibit outstanding damage tolerance and out-of-plane load capability.

The compression after impact test results for a stitched uni-woven fabric flat panel made with conventional brittle epoxy resin shown in Figure 7 exhibit a failure strain far above the accepted design

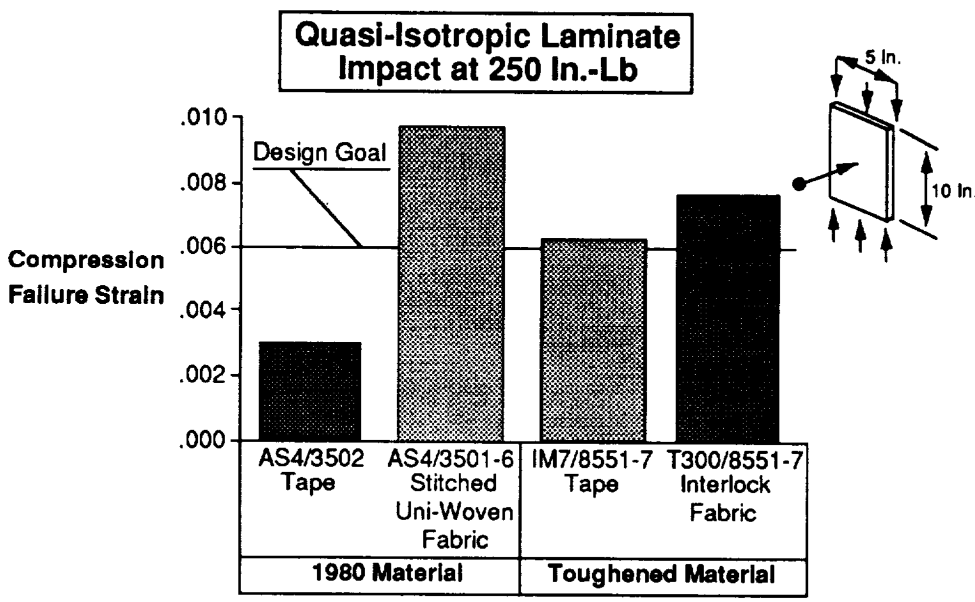


Figure 7. - Standard compression after impact for quasi-isotropic laminates, impact at 250 in-lb.

goal of 0.006% (11). Stitching provides the lowest cost highest productivity approach for through-the-thickness reinforcement of low cost 2-D fabric preforms. These preforms can be stored indefinitely at ambient conditions and resin transfer molded on demand with low cost two part epoxy matrix systems.

Douglas Aircraft Corp. is developing the technique for constructing stitched dry preforms from uni-weave fabric subelements illustrated in Figure 8 (15,16). The matrix used in the Douglas process is

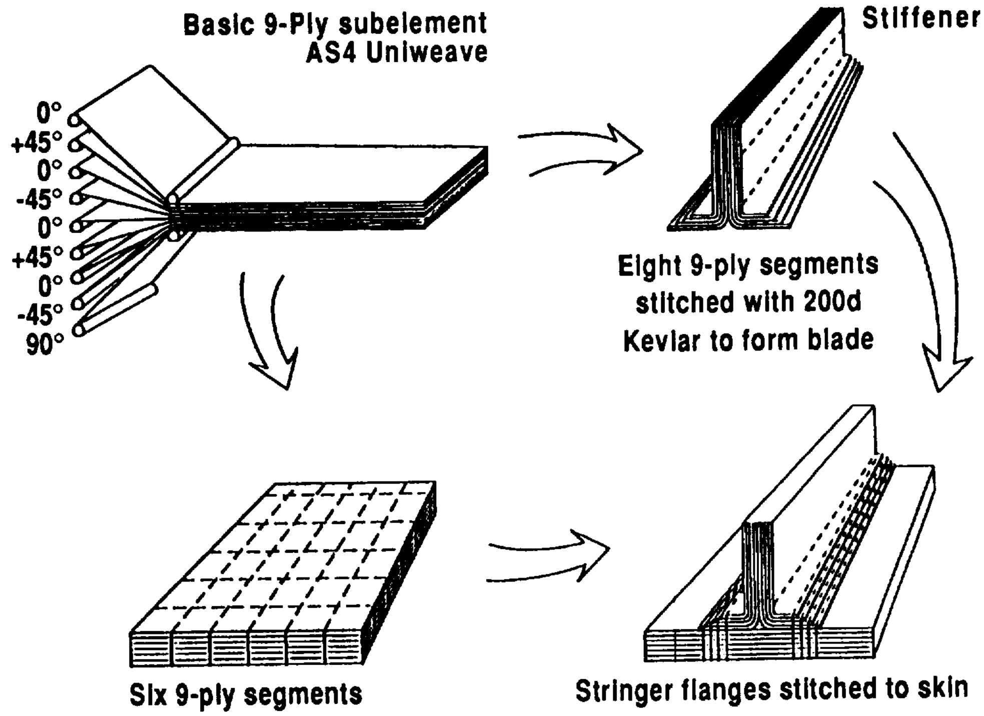


Figure 8. - Damage-tolerant stiffened panel concept.

either vacuum or pressure infiltrated into the preform which is bagged and cured using standard autoclave procedures. Damage tolerant single and triple blade-stringer panels have been fabricated from dry stitched preforms with conventional epoxy RTM. A 22-inch-wide by 22-inch-long three-stringer panel demonstrated excellent post-impact compressive strength as shown in Figure 9 (15).

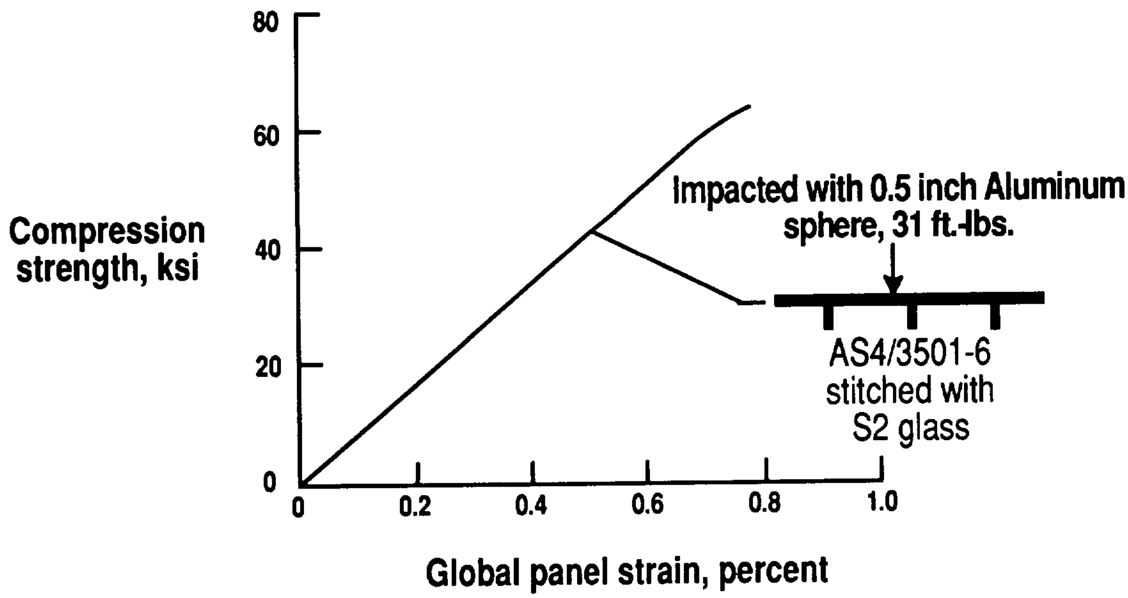
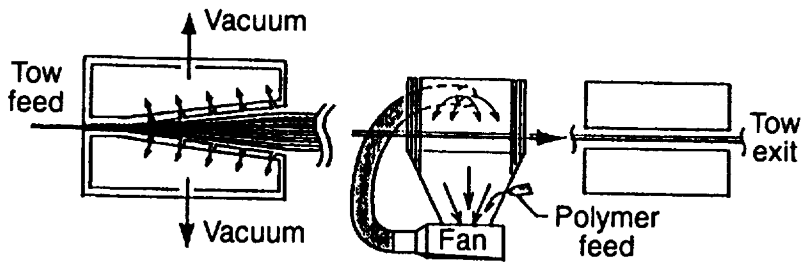


Figure 9. - Post impact compression strength of blade-stiffened panel.

Alternate methods to impregnate fibers with resin while maintaining the textile preform concept are being developed. Powder coating processes that homogeneously apply a polymer powder to 3K to 12K carbon tow offer promise as low cost towpreg that can be woven into fabric. The coating process is relatively simple and involves a tow spread chamber, a powder recirculating chamber, and a convection



Prepreg Processing Modules

Tow spreader chamber

- Adjustable tow spread
- Minimum fiber damage
- Fast line speed

Powder coater

- Recirculating chamber
- Uniform coating
- Precise resin control

Powder fusion

- Convection furnace
- Individual fiber coating

Figure 10. - Dry powder prepregging.

furnace for powder fusion as shown in Figure 10 (17). Advantages of powder-coated towpreg as a new method to combine fiber with resin are given in Table 2. It is especially useful for thermoplastics which

- Versatile: thermoplastics and thermosets
- Room temperature
- No solvents involved
- Minimum exposure to toxic materials
- Prepreg requires no refrigeration: cuts waste/spoilage
- Prepreg can be woven, filament wound, pultruded, thermoformed
- Good alternative to RTM processing of textile preform composites

Table 2. - Importance of the powder coating process.

otherwise are difficult to prepreg onto carbon fiber without the use of difficult hot/melt or solvent coating procedures. The mechanical properties of unidirectional and woven composites made from powder-coated towpreg show promising results (18).

Manufacturing Methods

ACT program participants are developing lower cost starting materials that do not add to down stream manufacturing cost, significantly more automation that will reduce labor cost and eliminate scrap due to human error, simple designs that exploit automated processes, approaches to eliminate autoclave consolidation requirements and assembly processes that eliminate shimming. Specific processes and methods that are being investigated include building block textile preforms, resin transfer molding, advanced fiber placement and braiding. Through-the-thickness stitching of uniweave tape and two-and three- dimensional woven or braided structural shapes offer the potential for automated equipment construction with indefinite ambient conditions storage. Braiding will be evaluated for building structural elements such as frames, spars and longerons and for fabricating large components such as a wing box.

Designers are beginning to develop design concepts that exploit the potential to reduce cost with new fabrication methods and automated fiber placement processes. Automated fiber placement is a process that provides inprocess consolidation of multiple ribbonized prepreg tows and uses robotic machine technology to control tow dispensing, location and direction. Individual towpreg ribbons have cut and add dispensing control so that each tow in a 32 tow band can be applied or removed without stopping the delivery head as it applies material. Automated fiber placement machines can be used to fabricate integrated structures by rapidly placing towpreg on complex shape tools or mandrels. Stiffeners can be wound into grooves in a mandrel that are oriented in any suitable stiffener orientation and then the skin is wound over the stiffeners to produce a stiffened shell structure with minimum part count, tool requirements, and a single cure cycle for the complete part. An ACT contract with Hercules Inc. (19) will use their automated fiber placement equipment shown in Figure 11 to demonstrate the cost effectiveness of the process to

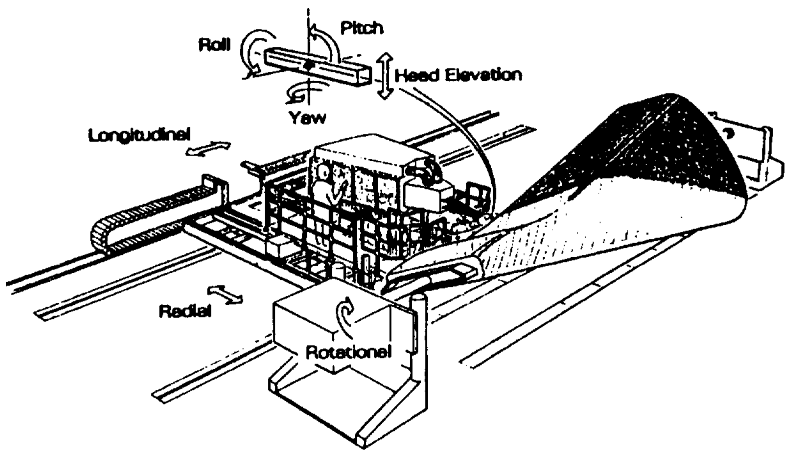
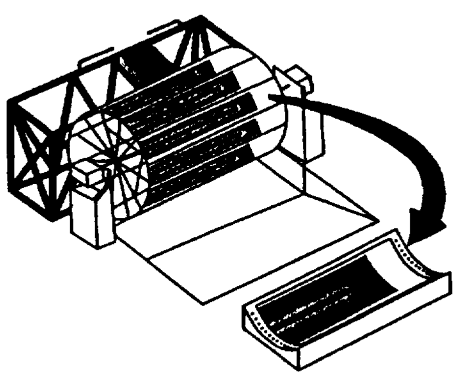


Figure 11. - Multi-axis fiber placement machine.

fabricate multiple panels similar to the Boeing fuselage keel quadrant panels shown in Figure 12. Advantages of the fiber placement process are provided in Table 3.



- Minimize splices and part count
- Automated batch processing
- Efficient ply tailoring
- Low-cost material form
- Compatible with all design families

Example: Keel quadrant skins

Figure 12. - Process efficiency of quadrant approach

- Ply thickness control
  - Thin plies, prepreg tape equivalent
  - Constant thickness
- In-process compaction
- Controlled fiber angles
  - Nongeodesic paths
- Potential low cost material form
  (In-line prepreg tow)
- 360° part fabrication
  - Longitudinal joint elimination
  - Fastener reduction

Table 3. - What fiber placement offers.

Summary

NASA, DARPA (20), DoD and industry all are seeking lower acquisition cost approaches to applications that will extensively increase the volume usage of composites in the next decade. Trade studies in Phase A of the ACT program have indicated that several composite manufacturing approaches will provide substantial weight savings at equal cost to aluminum for large primary structure. As composites processes are optimized and low cost textile material forms are introduced to the market place, composites will be less expensive than equivalent metallic structures. Cost effective composites will broaden opportunities for introduction of fatigue and environmental degradation resistant materials that exhibit near zero thermal expansion coefficient to broad sectors of industrial, commercial, automotive and sporting goods applications.

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