N93-30864

ADVANCED FIBER PLACEMENT OF COMPOSITE FUSELAGE STRUCTURES

Robert L. Anderson, Hercules Aerospace
Manager, Composite Structures Programs
Hercules Composite Structures Group

Carroll G. Grant, Hercules Aerospace
Program Manager, NASA ACT Contracts
Hercules Composite Structures Group

ABSTRACT

The Hercules/NASA ACT program will demonstrate the low cost potential of the automated fiber placement process. Hercules fiber placement machine has been developed for cost effective production of composite aircraft structures. The Hercules fiber placement process uses a low cost prepreg tow material form and achieves equivalent laminate properties to structures fabricated with prepreg tape lay up. Fiber placement demonstrations planned for the Hercules ACT program include fabrication of stiffened test panels which represent crown, keel, and window belt segments of a typical transport aircraft fuselage.

Hercules fiber placement has been selected for evaluation by other participants in the NASA ACT program. Douglas Aircraft has selected Hercules fiber placement for their ICAPS program. Several stiffened test articles varying in size from 21-in. × 36-in. flat panels to 4-ft to 5-ft curved panels will be fabricated and tested for comparison with similar RTM panels.

Boeing Commercial Airplanes will also evaluate fiber placement for their ATCAS program. The ATCAS test panels are 110 in. × 26 in. and have three co-cured stringers. Each panel has ply drops in the skin laminate that reduce thickness from 24 plies to 12 plies.

HERCULES ADVANCED FIBER PLACEMENT

Hercules began the development of fiber placement technology for the automated placement and in-process consolidation of ribbonized prepreg tow in 1980. In 1983, our first machine (FPM1) was operational and was used to manufacture flat panels, curved panels, and 360° cross sections, including stiffened and unstiffened skins.

Hercules fiber placement process makes use of robotic machine technology to provide an automated fabrication process for complex-shaped, high performance composite structures (Figure 1). The process involves the precise automated placement and in-process compaction of ribbonized prepreg tow. Multiple tows are laid down as a band with band location and angle precisely controlled. Material cut and add features, incorporated into the process, provide high production rate potential, enhance design tailorability, and minimize material scrap.

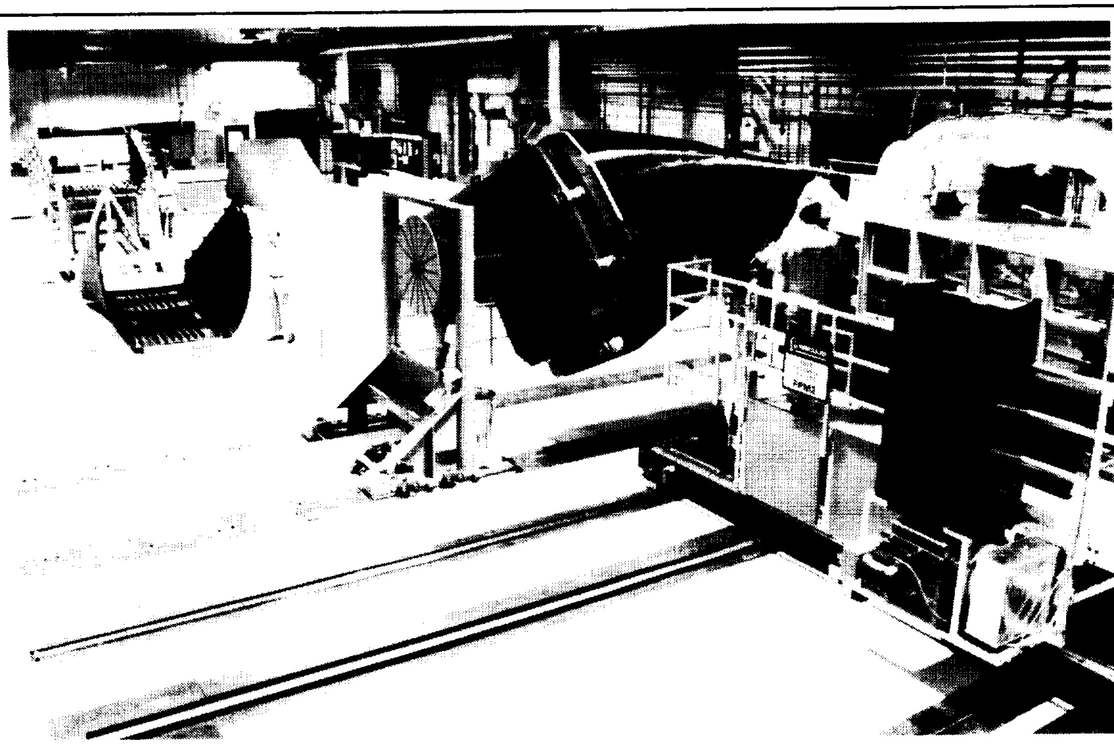


Figure 1

Hercules has successfully demonstrated the capability to fabricate a wide variety of complex structures using this technology. Aircraft wing components including ribs and spars, air inlet ducts, and fuselage structures have been successfully fiber placed.

Hercules currently has two operational fiber placement machines. FPM1 is a six-axis machine that has the capability to manufacture structures with a 20-ft maximum length and 11-ft maximum swing diameter. Our new production rated machine (FPM2 shown in Figure 1), which became operational in early 1990, is a seven-axis machine that has the capability to manufacture structures with a 33-ft long and 15-ft swing diameter. The first two MANTECH V-22 Aft Fuselage structures were manufactured on FPM1 and the third fuselage structure was manufactured on FPM2. Figure 2 shows a typical FPM2 setup with an explanation of the various axes of motion.

These fiber placement machines use a computerized mathematical model (Figure 3) of the part to generate a fiber path of a specified width, thickness, and orientation and to control tow cut and add functions. The software and hardware provide synchronization control and movement. The material delivery system processes, delivers, and compacts the prepreg tow material on the mandrel as demanded by part geometry.

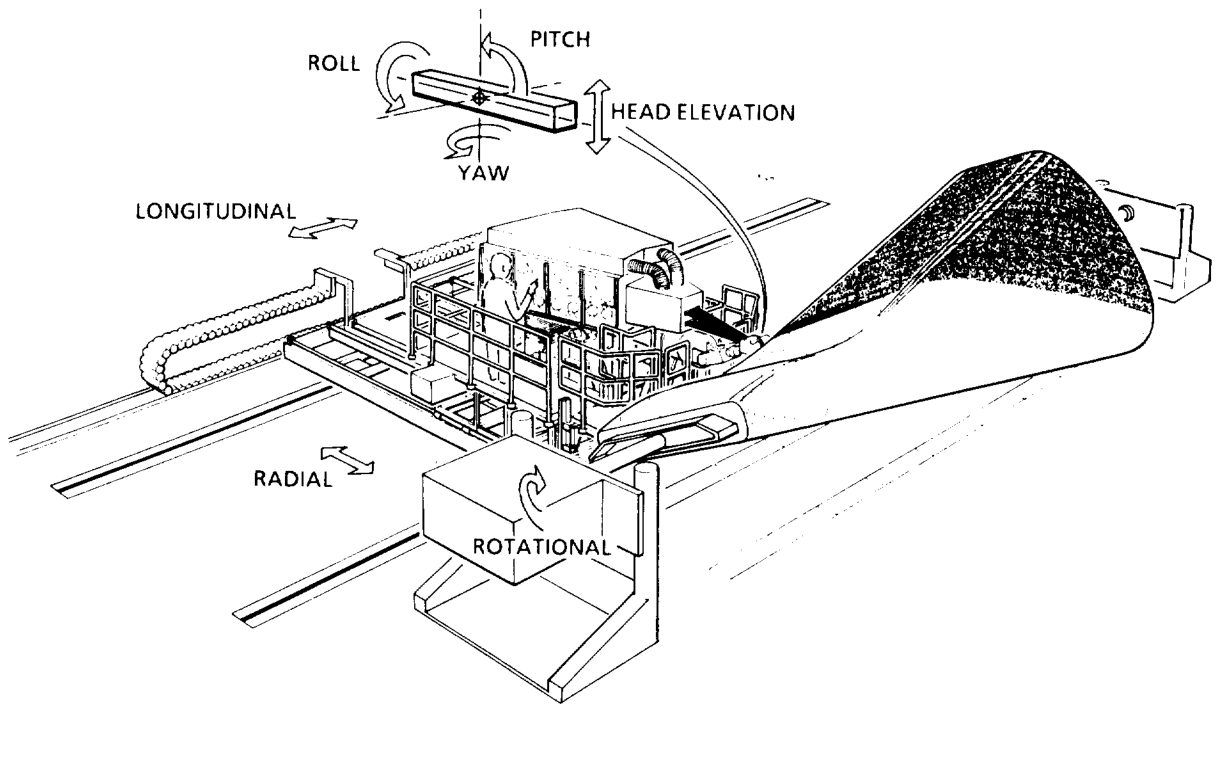
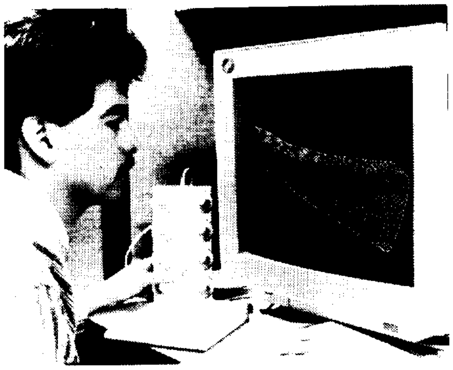


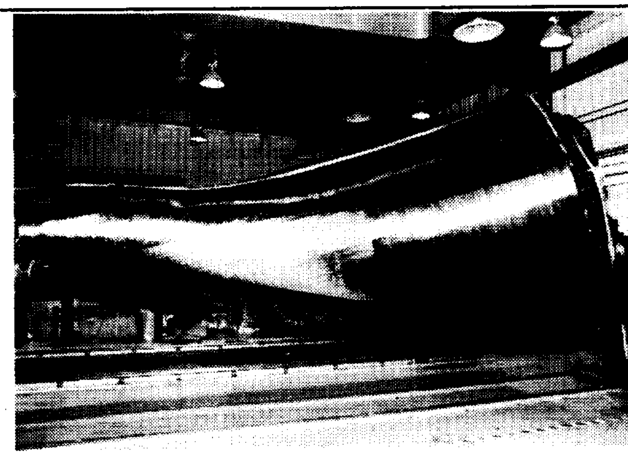
Figure 2. Multi-axis fiber placement machine

We currently have two delivery head designs that are operational on our fiber placement machines. The tow cut and add head allows for individual tow cutting and adding for ply tailoring on complex, nongeodesic structures. The band cut and add head is used for all structural shapes that do not require individual tow cut and add capabilities. Both of these delivery heads are designed for 12 tows. We also have a tow cut and add head that is designed for 32 tows. The 32-tow head was used on the MANTECH V-22 Aft Fuselage shown in Figure 1.

Fiber tow placement offers many improvements over hand lay up that contribute directly or indirectly to cost savings. Tow width control allows for non-standard ply thicknesses which optimize part design while maintaining constant band width. Gaps and overlaps are kept within a tolerance of 0.75 mm (0.030 in.). Constant ply thickness can be maintained by adding or dropping tows as the part changes cross section (Figure 4). Tow and band cut/add features reduce material scrap to as low as 5% by placing the material only where required. Fiber placement also uses prepreg tow that is projected to be the lowest cost material form available. The tow-placed product is also comparable in performance to hand lay up prepreg tape parts (Figure 5).

During the fiber tow placement process, a conformable roller rides directly on the part or tool, providing in-process compaction while delivering the tow material. This minimizes the need for intermediate compaction steps. The placement head flexibility allows fiber placement on convex and concave surfaces. The delivery head delivers individual tows as a flexible band to minimize material distortion. This flexibility provides fiber angle control that allows for fiber placement of non-geodesic shapes which cannot be fabricated with filament winding (Figure 6).





- Models 3-D surface
- Calculates 3-D fiber paths
- Calculates machine positions to deliver the fiber
- Translates machine positions into a control table
- Can generate program from customer tooling

The fiber placement control program provides instructions for a multi-axis machine to deliver material on a precise path over a complex 3-D surface.

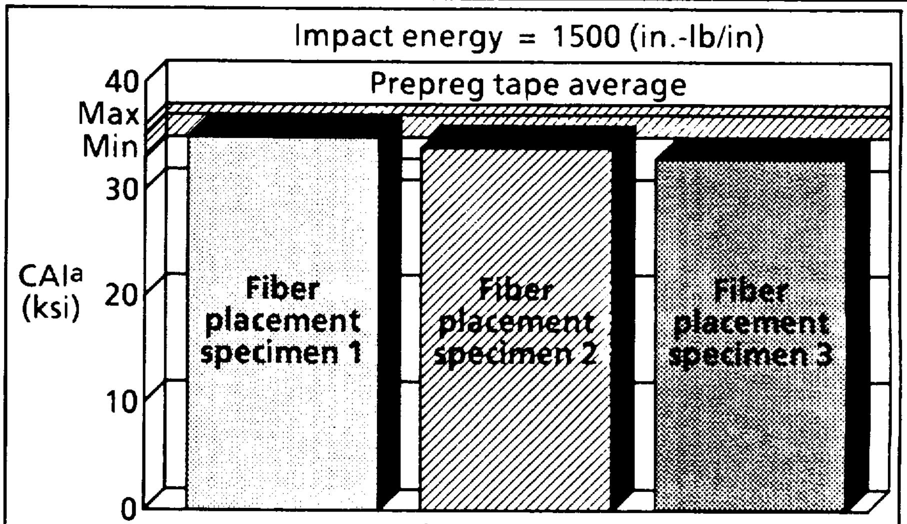
Figure 3. An off-line programming system generates fiber placement paths based on mathematical model

The winding angle is not limited. Axial (0°) plies can be readily placed with this process.

FIBER PLACEMENT OFFERS STRUCTURAL PERFORMANCE ADVANTAGES

- Ply Thickness Control
  - Thin Plies (to 5 mils), Prepreg Tape Equivalent
  - Control Independent of Geometry
- In-Process Compaction
- Void Volume 1% or Less
- No Limitation on Fiber Angles
  - Tailored for Design Requirements
  - Nongeodesic Paths
  - Convex or Concave
  - Capable of Helical, Hoop, and Longitudinal Orientations

Figure 4.



a. Compression after impact tests

- Damage tolerant IM7/8551-7A towpreg demonstrated
- Fiber placement process CAI results demonstrate equal quality to prepreg layup process
- Concave surface, variable skin thickness, tapered cross section and thin ply laminates now possible with automated process

Figure 5. Compression after impact test data

Item	Filament Winding (Wet)	Fiber Placement (Prepreg Tow)
Void content	4-8%	<1%
Thickness	• 0.010-0.025 in/ply • Not constant for tapered parts	• 0.005 - 0.015 in/ply • Constant for tapered parts
Tow cut and add	No	Yes
Winding angle	>15° 15 - 90°	No limit 0 - 90°
Laps and gaps	0.125 in.	0.030 in.
Geometry	Best for bodies of revolution	• Complex • Concave
Scrap rate	20 - 40%	5 - 20%

Figure 6. Filament winding/fiber placement comparison

HERCULES NASA ACT PROGRAM

In early 1989, Hercules received a contract award from NASA LaRC to participate in the advanced composites technology program. The objective of the contract was to exploit the utility of Hercules fiber placement process to achieve low cost manufacturing of transport aircraft fuselage structure. The basic design selected by Hercules for this program was an isogrid-stiffened skin panel that would be fabricated in one fiber placement operation. The unidirectional tow stiffeners would be tow placed into cavities on a mandrel and the skin would be placed over the stiffeners (Figure 7). The skin and isogrid-pattern blade stiffeners would be co-cured in an autoclave using the mandrel as the cure tool.

The design for the isogrid-stiffened structure was to be provided by NASA LaRC. Hercules would conduct an in-depth study to resolve the critical issues of blade stiffener intersections (crossovers) and skin to stiffener interface.

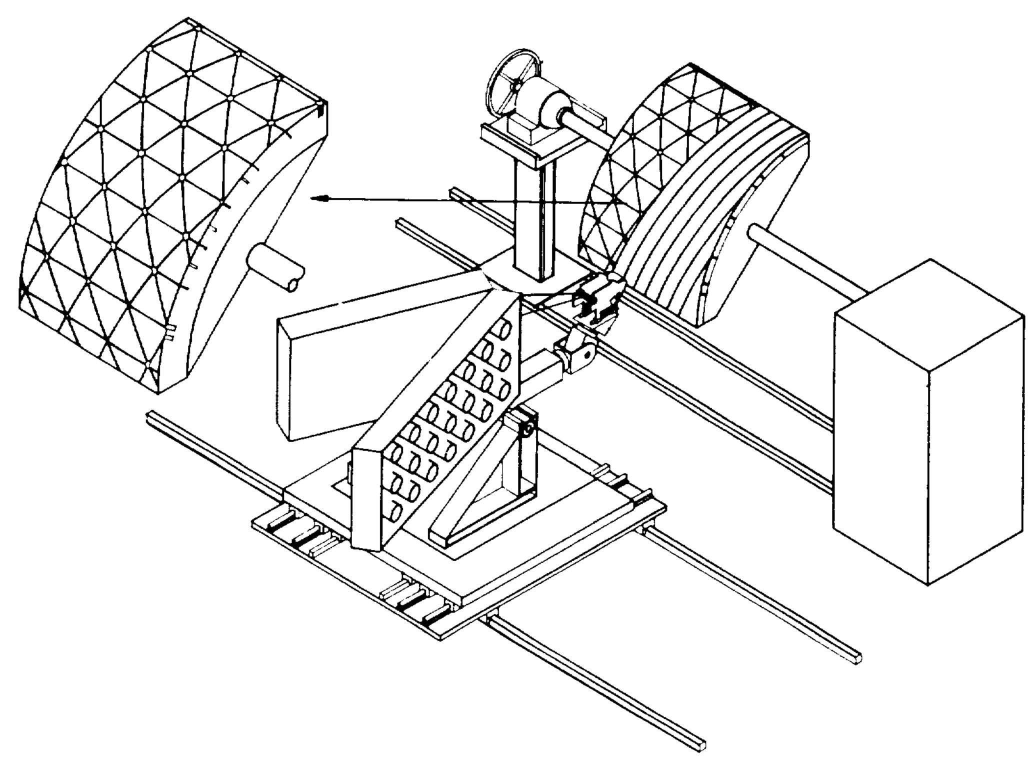


Figure 7. Isogrid panel in 7-axis (FPM2) machine

The Hercules isogrid-stiffened fuselage program was slow in getting started as NASA LaRC was unable to provide an acceptable stiffener design and there was some concern about producibility of the isogrid design with unidirectional tow.

In early 1990, NASA LaRC notified Hercules that the ACT program would be redirected toward a more conventionally stiffened fuselage structure. Several options were considered for the Hercules program and in April we were asked by NASA LaRC to work with Boeing to complement the ATCAS program.

The new Hercules program will be a cooperative endeavor between Boeing Commercial Airplanes and Hercules Incorporated. Hercules will fabricate test elements and panels representative in design of crown, keel and window belt quadrant of a typical Boeing Commercial transport aircraft. The fabrication process for all elements will be Hercules advanced fiber placement. Boeing will provide design and testing of all elements and panels on the Hercules ACT program (Figure 8).

Fuselage Quadrant	Test Article	Undamaged Elements	Tension With Damage	Shear With Damage	Comp. With Damage	Bi. Tension With Damage	Comp/ Shear With Damage
Crown	Flat, unstiffened skin panels (12 ft × 5 ft)		2				
Crown	Flat, stiffened panels (12 ft × 5 ft)		1				
Crown	Curved, stiffened panels (3.5 ft × 3.5 ft)					2	
Keel	Flat, coupons (5 in. × 7 in.)				24		
Keel	Flat, stiffened panels (3 ft × 2 ft)				6		
Keel	Curved, stiffened panels (3.5 ft × 3.5 ft)						1
Window belt	Tension coupons with thick taper (12 in. × 12 in.)	3	3				
Window belt	Curved panel with taper and cutout		1				
Window belt	Panel w/double window frame (3.5 ft × 3.5 ft)			1			

Figure 8. Test matrix for Boeing/Hercules ACT Program integration

HERCULES NASA ACT SUBCONTRACTS

Hercules advanced fiber placement process was identified for evaluation on several NASA ACT contracts (Figure 9). We currently have several subcontracts in process for fiber placement of various aircraft related structures. We are also discussing future subcontracts with other NASA ACT program participants. Our current subcontracts are with Boeing and Douglas. We have had discussions with Lockheed regarding fiber placement of stiffened wing skins and stiffened fuselage skins. However, at this time, sufficient detail about these subcontracts was not available to be included in this paper. We have also had preliminary discussions with Northrop about subcontracts on their ACT program, but due to redirection in the Northrop program, this has been delayed.

Boeing	DOE Panels Hybrid panels Crown panels
Douglas	Stiffened skin panels
Lockheed	Wing skin panels Fuselage skin panels
Northrop	TBD

Figure 9. Hercules ACT subcontracts

Boeing ATCAS Program

Hercules currently has three subcontracts in process from the Boeing ATCAS program. We are working on the DOE panels, graphite glass hybrid panels, and stiffened crown panels. The DOE panel and hybrid panel contracts are mostly complete; the crown panel contract is just getting started. Preliminary discussions have started regarding future subcontracts for window belt and keel panel fabrication. These contracts are for Boeing evaluation of the structural performance and cost effectiveness of the fiber placement process.

ATCAS DOE Panels

Hercules recently completed fabrication of eight flat stiffened DOE panels, four of these panels were 31 in. × 110 in. and four were 21 in. × 110 in. Three hat section stiffeners were used on four panels and three blade stiffeners were used on the other four. The panel skins (Figure 10) and stiffeners were fiber-placed materials. The stiffeners were kitted from fiber-placed panels and formed into hat and blade stiffeners. The skins taper in thickness from 24 plies to 12 plies down the length of the panel and the stiffeners taper from 16 plies to 8 plies.

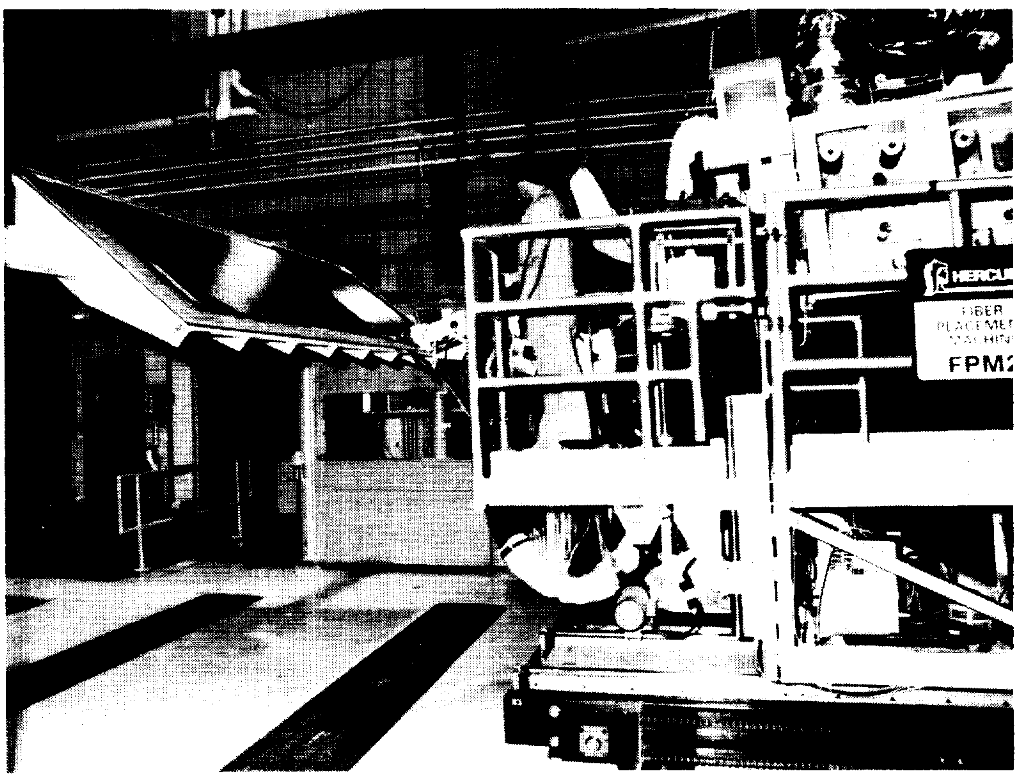


Figure 10.

The skin and stiffeners were assembled and co-cured in an autoclave. Four resin/fiber material combinations were used for fabrication of these panels: IM7/938, IM7/977-2, AS4/938, and AS4/977-C.

Fabrication of these DOE panels is complete and they have been delivered to Boeing for testing . (Figures 11 and 12.)

Figure 11. ATCAS DOE panels

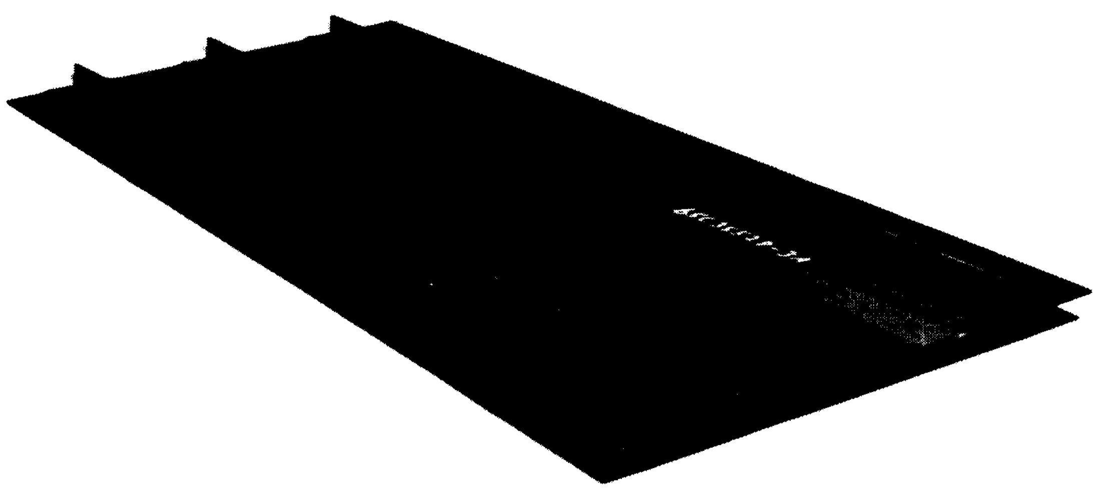


Figure 12. ATCAS DOE panels

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ATCAS Hybrid Panels

The Hercules fiber placement process was selected for fabrication of graphite/ S-2 glass hybrid panels. Because the fiber placement machine uses individual tows to form a band, the graphite to glass ratio can be varied. Seven panel configurations were fabricated for testing (Figure 13). Five of the panels were fabricated with different graphite to glass tow ratios and the sixth and seventh panels were each of a single material type. The panels were 10-plies thick and 22 in. × 68 in. dimension (Figure 14). Fiber types were AS4 (6K), T1000 G (12K), and S-2 glass (750 yield). The resin used was Fiberite 938 epoxy. As each hybrid configuration was set up in the machine, 5 lb of tow-placed tape was dispensed and sent to Stanford University as part of this contract.

Material	Fiber 1	Fiber 2	Adjacent Tows of Fiber 1	Adjacent Tows of Fiber 2
1	AS4	S-Glass	3	1
2	AS4	S-Glass	2	2
3	AS4	S-Glass	6	6
4	AS4	S-Glass	9	3
5	AS4	T1000G	9	3
6	S-Glass	None	NA	NA
7	AS4	None	NA	NA

Figure 13. Material definitions

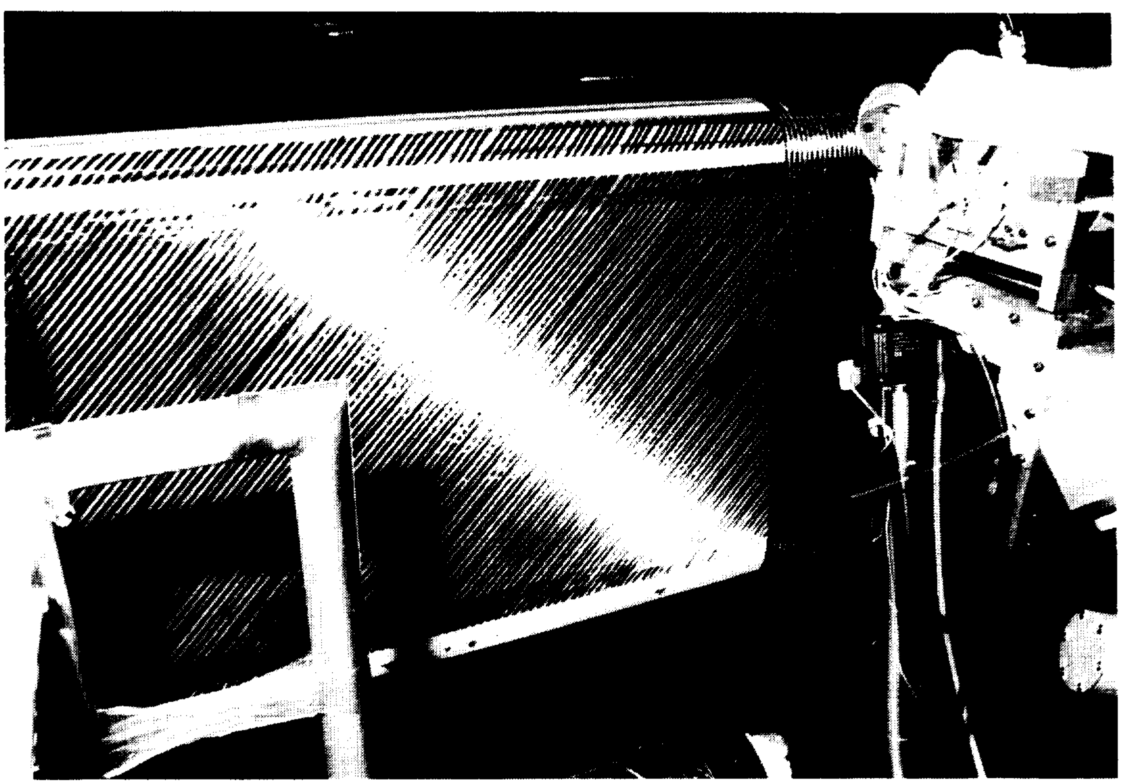

Figure 14.

ATCAS Crown Panels

Hercules recently received an ATCAS subcontract for fiber placement of three large crown panels. These panels will be representative in design of body Section 46 crown quadrant on the proposed Boeing 767-X aircraft and will be made in two basic configurations--skin/stringer/frame and core-stiffened skin. Materials will be a graphite/S-2 glass hybrid form.

To expedite this program, Hercules will use an existing large rocket motor mandrel for fiber placement of skins for two of the panels. A large fiber placement mandrel (Figure 15) is being designed for producing two crown panels approximately 8 ft × 9 ft in one operation.

The fabrication process for these panels has been demonstrated at Hercules recently and is a simple, low risk approach. Skins are fiber placed on a mandrel and transferred to an OML mold for cure. The pre-formed stringers are located to the IML surface of the skin and the assembly is vacuum bagged for autoclave cure. On the 8-ft x 9-ft panel, a thin graphite molded caul sheet will be used on the IML surface.

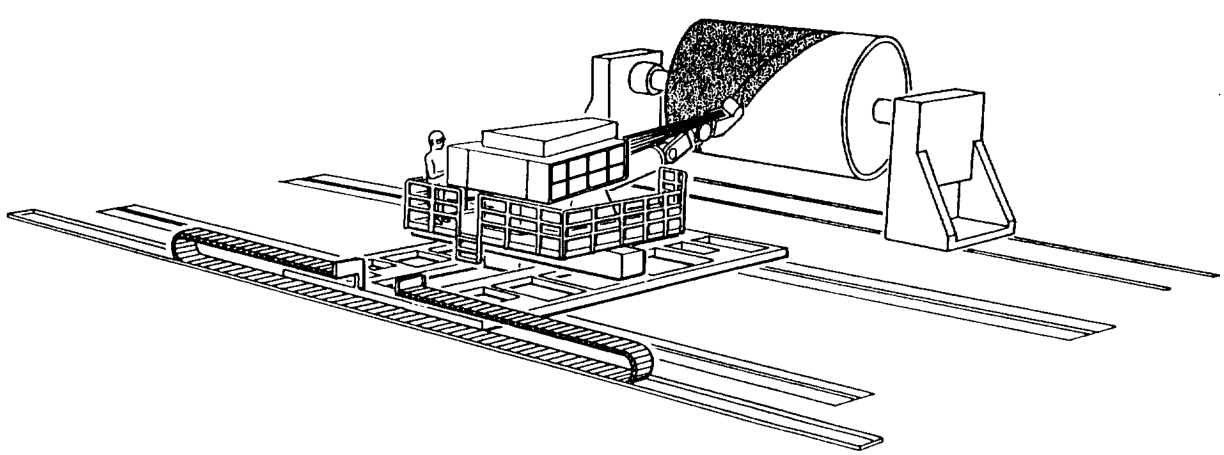

Figure 15.

Douglas ICAPS Program

Hercules currently has a large subcontract with the Innovative Composite Aircraft Primary Structures (ICAPS) program at Douglas Aircraft Company. The contract is for Douglas evaluation of the fiber placement process and specifically, to compare fiber placement with resin transfer molding (RTM) for structural performance and cost effectiveness. This program is approximately half completed; we are currently building tooling for the last deliverable parts.

Hercules ICAPS Panels

The Hercules ICAPS subcontract is for fiber placement of CAI specimens, 21-in. × 36-in. stiffened, flat element panels and 4-ft × 5-ft stiffened, curved subcomponent panels. A toughened resin system (8551-7A and 8551-7) was selected for this program to achieve maximum damage tolerance performance. Stiffeners for the element and subcomponent panels are hand formed J-stiffeners. The CAI specimens and element panels have been completed and delivered to Douglas. Fabrication of the large subcomponent panels will begin in late October.

A fabrication process was developed for the ICAPS element panels that proved to be low risk, cost effective, and produces consistent, high quality parts. The process uses the fiber placement machine, low-cost tooling, and stringer to skin cocuring. Skins are fiber placed on a mandrel that can be made with inexpensive, low temperature materials because it will not be subjected to a high temperature and pressurized autoclave environment. When the skins are complete, they are transferred to an OML cure mold that can be made of composite, steel, or aluminum. Stringers are fitted with aluminum cure mandrels and located on the IML surface of the skin with the aid of a picture frame location template. A thin, flexible caul sheet with molded cavities for the stringers is positioned to the IML surface of the panel assembly (Figure 16). The "flex caul" is 3- to 4-plies thick and is fabricated from a master model. The assembly is vacuum bagged and autoclave cured. The result is a panel with a smooth, aerodynamic OML surface and a "finished" IML surface as well. Seven stiffened element panels were fabricated with this process and quality consistency was remarkable (Figures 17 and 18).

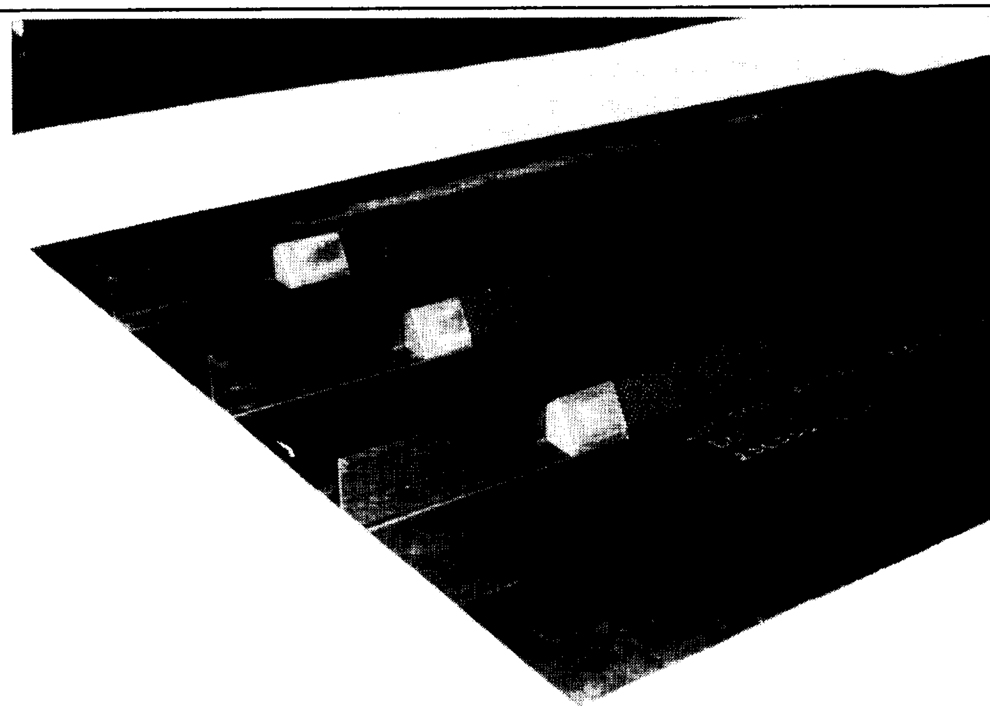

Figure 16. ICAPS element panel photo flex caul

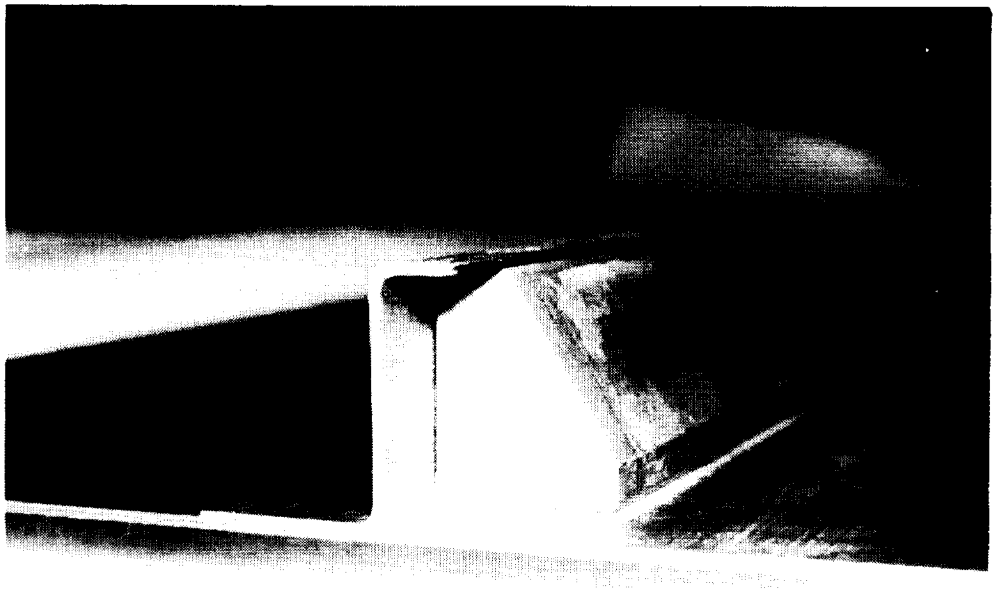

Figure 17. ICAPS element panel photo

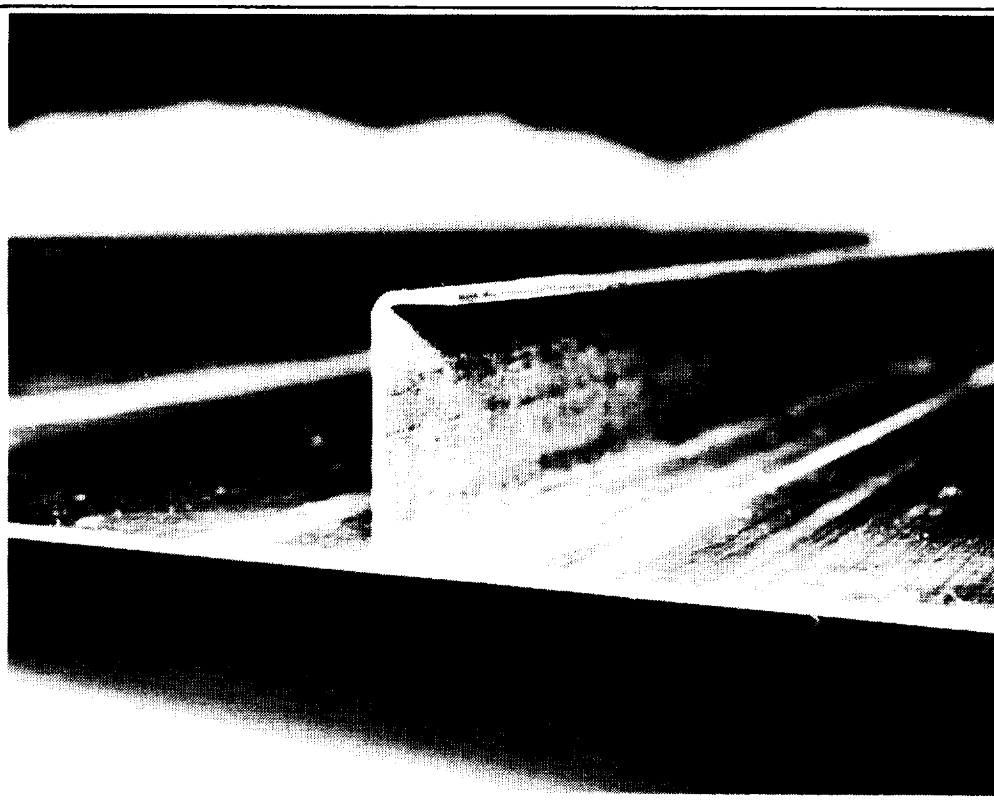

Figure 18.

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The "flex caul" process will be used on the 4-ft × 5-ft curved subcomponent panels that will be fabricated later this year and in early 1991. These parts will close out our current ICAPS subcontract. We have had discussions with Douglas about future NASA related projects that we may be involved in.

Summary

At the time of this paper, Hercules has had discussions with Lockheed and Northrop about fiber placement subcontracts, but programs were not sufficiently defined to include in this paper. We look forward to demonstrating Hercules fiber placement to both Lockheed and Northrop and continuing to provide fiber placement evaluation requirements of the Boeing ATCAS and Douglas ICAPS programs as well.

Hercules is excited to be a part of the NASA Advanced Composites Technology program and we appreciate the opportunity NASA has given us to demonstrate fiber placement to the aerospace community.