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# AFFORDABLE THERMOPLASTIC PROCESSING OF MARINE STRUCTURES

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## ABSTRACT

The Advanced Research Projects Agency (ARPA) initiated a major technology effort to develop and demonstrate cost effective, advanced fabrication methods for marine structures. In-situ consolidation of thermoplastic composite structures in concert with automated fiber placement offers the premise to produce affordable, high quality parts. In-situ consolidation processing eliminates costs due to hand layup, bagging and autoclaving as well as costs associated with acquiring, operating and maintaining an autoclave. Automated fiber placement with high quality and tight dimensional control offers the ability to make complex parts, to lay materials at any fiber angle and path, to vary bandwidth and to cure using in-situ consolidation. This paper will present process related issues associated with the thermoplastic, hot gas, in-situ consolidation of 61 cm diameter cylindrical demonstration models, NOL rings and test specimens to achieve low manufacturing costs. These process related issues include process adaptation, throughput, part integration and scalability to larger diameter parts. Optimization of these factors in terms of manufacturing costs and quality (void content, mechanical properties) will enhance the development of the in-situ consolidation fiber placement process into an affordable manufacturing technology. Thermoplastic materials investigated included carbon/PEEK and carbon/PPS. This work was sponsored by the Maritime Systems Technology Office, Advanced Research Projects Agency.

Keywords: Fiber Placement, In-situ Consolidation, Marine Composites, Thermoplastics

## 1.0 INTRODUCTION

The use of composite materials in lieu of existing metals offer the potential for reducing weight, reducing maintenance and enhancing stealth and survivability of submersibles and marine structures. However, the composites selected must also demonstrate their benefits at competitive costs with their replacement. In order to be competitive, low cost innovative material forms and low cost manufacturing and design concepts must be developed for composites while achieving the high quality levels demanded for man rated marine structures. Recognizing the benefits of composites, ARPA has initiated a major technology effort in developing and demonstrating affordable composites fabrication processes for marine applications. Emphasis was placed on the use of advanced automated fabrication methods such as fiber placement in concert with in-situ consolidation of thermoplastics.

The in-situ consolidation automated fiber placement process and real time in-process control may be the most effective solution to alleviate the high costs and quality deficiencies associated with hand layup, filament winding, bagging and autoclave cycles. Precise automated placement of fibers with multiaxes winding over complex mandrels will permit continuous, rapid, reproducible fabrication of marine structures with relatively high throughputs and near zero porosity and precise resin control without the use of vacuum bagging and autoclaving. Furthermore, the costs involved in acquiring, operating and maintaining an autoclave are eliminated as well.

In terms of thick walled marine structures, the in-situ consolidation fiber placement process does not require any debulking steps during fabrication due to the fact that the material is fully consolidated as it is placed on the structure. Expensive high temperature tooling may also be eliminated.

The material system selected must also be compatible with the fabrication process. Thermoplastic crystalline material systems, AS4/APC-2, AS4/PPS were selected to satisfy the operational and safety requirements. These include strength, stiffness, fatigue resistance, chemical/corrosion resistance, damage/durability performance, moisture resistance, repairability and fire, smoke and toxicity (FST) requirements [1] [2].

This paper will discuss the advantages of the thermoplastic fiber placement technology using hot gas in-situ consolidation process and process related issues which directly influence the manufacturing costs. The process related issues which will be addressed include process adaptation, throughput, part integration and scalability to larger diameter parts. Current applications of the in-situ fiber placement process for the fabrication of thermoplastic carbon/PEEK and carbon/PPS for the Advanced Research Projects Agency's Composite Dry Deck Shelter Program will be discussed.

## 2.0 THERMOPLASTIC FIBER PLACEMENT

### 2.1 Process

One low cost, automated fabrication technique lending itself to both thermoplastic and thermoset materials is fiber placement. The advantages of fiber placement include the ability to make large complex structures like submersible hulls, to lay material at any fiber angle and any path and the ability to vary bandwidth. Precise, automated placement of fibers with multi-axes winders over complex mandrels and with in-situ consolidation will permit continuous, rapid, reproducible fabrication of marine structures with relatively high throughputs and low porosity and precise resin control without use of on line vacuum bagging and autoclaving. In-situ consolidation will ultimately be coupled with real time in-process control and will result in less rework and rejects of finished parts. Thermography and laser interferometric detection appear to be well suited techniques for real time identification of existing flaws and damage for filament wound/fiber placed configurations. The system can then identify anomalies before consecutive plies are wound over the flaw. Embedded sensors, if incorporated, will also assist in determining composite quality and for future health predictions.

Auto consolidation of thermoplastics using fiber placement is being pursued by McDonnell Douglas Aerospace, Lockheed and General Dynamics/EBDiv for the ARPA Composite Dry Deck Shelter Program. Details of the ARPA CDDS program are given in [3] [4] [5]. The thermoplastic fiber placement processing utilizes heat energy to simultaneously melt incoming feed material and the surface of the previously consolidated material as illustrated in Figure 1. A pressure applicator then consolidates the thermoplastic in-situ and requires no further oven or autoclave processing. On line Non Destructive Inspection, NDI, sensors track behind the applicator to provide real time in-process control.

The program participants are investigating different heat sources and placement heads to achieve the quality, performance and cost requirements of the program. Lockheed has developed a multi-tow hybrid hot gas/hot shoe tape head for use with AS4/PPS prepreg tape [5]. McDonnell Douglas Aerospace has utilized a five axes machine with automated band cut and add head for use with axial and off-axis tow placement and uses laser energy as the heat source for their program deliverables [6]. This paper will emphasize the development of the prototype fabrication of the thermoplastic stiffened, cylindrical sections and test articles being performed by General Dynamics/EBDiv with ICI Composite Structures and Automated Dynamics Corporation. Hercules Composite Structures is supporting ICI/ADC in the fabrication, testing and producibility evaluations.

The equipment consists of a thermoplastic processing head (TPP) developed by ADC which uses nitrogen gas in a patented Hot Gas Torch to elevate the temperature of the matrix in the incoming tape or tow and the previous ply while being compacted by the compaction roller (Figure 2). Nitrogen gas is used to prevent oxidative degradation during the consolidation process. This process does not depend on incoming fiber tension. Consequently, material can be placed on open section geometries which have a single, double, or an infinite radius of curvature. The automated tape cut and splice capability of ADC's fiber placement heads results in several unique features which can be utilized during part fabrication which reduce cost and improve part quality. True axial reinforcement can be achieved on cylindrical geometries, without any special tooling requirements, such as pins located in the turnaround regions. Helical plies can be placed with or without fiber crossovers. Accordingly, helical plies are not limit to biaxial plies. A positive or negative helical ply can be placed independent of one another. Ply drop-offs/build-ups can be placed within a structure. Also, within a ply, a tape path can be started or stopped to enhance wall thickness uniformity. This feature proves to be beneficial for closed geometries with nonconstant cross-sections. Furthermore, tape splices can be strategically located within a ply such that failure locations can be designed into the structure.

### 2.2 Modeling

In assessing the differences between auto consolidation and autoclave cure, mathematical models were developed. Initial basis for the model came from Lee and Springer's work on isothermal thermoplastic consolidation [7]. A rate form model was developed which enabled consolidation for any arbitrary process history. Since we are dealing with extreme heating rates, the additional effects of material degradation were added to the model as well as realistic manufacturing conditions of interply void formulation and partial interply autohesion. All processes are assumed to be thermally activated. Lee and Springer's model assume a two stage process by which consolidation is assumed to occur through first achieving intimate contact between plies followed by the molecular diffusion of the polymer from one ply into the other defined as autohesion.

Figure 3 shows the temperature history for an assumed fabrication sequence for AS4/APC-2. This simplified process simulation assumes a linear heating profile to the indicated temperature in the specified time period. The bottom two curves are for two different pressures used during the simulation. The lower curve is for one atmosphere pressure while the higher curve correspond to 0.1 atmosphere. Full consolidation line corresponds to using one atmosphere of pressure throughout the indicated consolidation process. The process window is defined as the region between the point that full consolidation is achieved and the initiation of unwanted thermal degradation. Full consolidation corresponds to state of maximum interply bond strength. For the in-situ consolidation process times (0.01 to 0.1 sec) the predicted process window is quite large for the short process times which should translate into very favorable processing conditions for on-line thermoplastic processing. Autoclave processing would correspond to the 3000 to 8000 seconds process times. Similar trends can be derived for AS4/PPS. However, the process temperatures are lower for PPS making the material system easier to process than APC-2.

Figure 4 depicts the empirical relationship between the degree of bonding and compression strength for AS4/APC-2. The model shows that full compressive strength is achieved at about 75%. The model, however, did not account for the effect of porosity/void content which has a more pronounced effect on the other material properties as shown in figure 5 obtained from Ghiorse [8]. In the autoclave process the long temperature/pressure cycle insures removal of most porosity. For the in-situ consolidation, process parameters and supplier prepreg void content quality are more critical in insuring zero porosity and must be carefully monitored.

## 2.3 Residual Stresses

Thermal residual stresses due to autoclave manufacturing produce an adverse affect on the fatigue life and strength of structural components due to their large magnitude and are usually considered in the design of the structure. This condition is further aggravated and complicated for thick walled marine structures which are usually filament wound, debulked and autoclaved. Analytical investigations indicate that the through-thickness stresses are significantly reduced for thick walled cylinders fabricated by the in-situ consolidation process as compared to those fabricated by a typical thermoset autoclave process. Figure 6 shows the measured residual stresses obtained by Joh using Moire Interferometry [9] on circumferentially fiber placed, auto consolidated, rings manufactured by McDonnell Douglas Aerospace. Residual thermal stress is shown as a function of thickness and tool temperature for a small radius ring of AS4/APC-2. Residual circumferential thermal stress at the inner radius is shown to be negligible for the unheated tool. The residual stress at the outside surface is about half as large as the inner surface stress and compressive. Good agreement has been obtained between Moire Interferometry results and analytical calculations based on the measured opening after cutting the rings to relieve the residual stresses. Other investigators [10] have shown similar residual stress reductions of in-situ consolidation over autoclave cure.

## 3.0 Costs Affecting Process Development

In working to achieve the high quality and high throughput goals of the ARPA program, ICI/ADC is performing on-going research and development activities to continuously improve the in-situ consolidation process. These activities consist of both process development and equipment development efforts. Process development efforts are aimed at maximizing the level of consolidation and determining the sensitivity of process parameters, while equipment development efforts are aimed at improving the economics (throughput) of the in-situ consolidation process.

Knowing the cost versus performance relationship, the appropriate in-situ consolidation fiber placement process can be selected to optimize performance while reducing manufacturing costs.

## 3.2 Throughput

Throughput can be defined as the rate at which the material is processed and is typically stated in kg/hr (lbs/hr). Throughput is a function of placement velocity, material form and equipment configuration.

The rate at which material can be placed and in-situ consolidated is limited by the physical phenomena which are required to occur, such as matrix flow and molecular diffusion. Even through this limit has not been practically ascertained for the fiber placement technology under consideration, any increase would prove to be beneficial especially when the other scale-up factors are considered.

Fabrication process material performance is measured by determining the mechanical properties obtained from representative element tests. For the fiber placement in-situ consolidation, performance data is based on implosion and burst rings, NOL rings and JANNAF (Joint Army Navy NASA Air Force) tubes. However, as discussed earlier, and shown in Figure 5, the interlaminar shear strength is the most sensitive to process parameter variations such as placement rate since it depends on the matrix bond between adjacent plies. Measurement of the interlaminar shear strength by the short beam sheart test method (ASTM D2344) is a cost effective screening tool for gaging the consolidation quality of the fiber placement process. The effect of placement rate on the interlaminar shear strength for AS4/APC-2 material system is shown in Figure 7 and for AS4/PPS in Figure 8 for NOL rings. Because of the operational and quality requirements, throughput rates of 3 to 4 cm/sec for AS4/APC-2 and 12 to 20 cm/sec for AS4/PPS were investigated for test articles to produce autoclave type properties. The PPS material system is able to be processed at much faster rate than the APC-2 system.

The form of the material can be changed in width and/or thickness such that a greater volume of material can be processed. For example, APC-2/AS4 is produced as a 30,5 cm (12 inch) wide tape. Currently, this 30,5 cm wide tape is slit into smaller widths such as 0,6 cm (1/4 inch) widths. The placement of 30,5 cm wide tape with either a wide-tape head or a multi-tow head would result in an increase in the throughput by a factor of 48 relative to that of 0,6 cm wide tape. Table 1 compares the effect of different width tapes on the interlaminar shear strength and void content for AS4/APC-2 NOL rings processed at the same rate. From the preliminary process development studies tape widths of 2,54 cm were selected to produce lower void content and improved interlaminar shear strengths.

TABLE 1. TAPE WIDTH EFFECTS FOR AS4/APC-2

| Material Width (cm) | Void Content (%) | ILS (MPa) |
|---|---|---|
| 0,6 | 5,3 | 73,1 |
| 2,54 | 2,9 | 90,3 |
| 7,62 | 3,0 | 82,7 |

In addition to increasing the tape width, the thickness of the tape can be increased as well. If a 0,5 mm material form is processed a factor of four increase would be realized. This material form could either be achieved by manufacturing a 0,5 mm thick prepreg or by guiding four 0,12 mm thick tapes into the placement head. In combination, that is, 30,5 cm wide tape with a 0,5 mm thickness, the throughput rate would be increased by a factor of 192 over that of 0,6 cm wide tape test articles. Together these two approaches to improving throughput could significantly enhance material processing rates and reduce fabrication costs.

Even though the fiber placement process has been successfully demonstrated for tapes up to 7,6 cm wide, the scale-up of the in-situ consolidation process for 30,5 cm wide material forms may incur some challenges. For example, maintaining a uniform temperature profile of the material across the 30,5 cm tape will be complicated by the different heat transfer characteristics of a 30,5 cm wide tape as opposed to that of a 7,6 cm wide tape. Edge effects and interior thermal build up may be significant. For the case of a thicker tape, 0,5 mm for example, heat transfer characteristic issues may arise again. For this case, maintaining the appropriate temperature profile through the thickness of the tape may become an issue. This profile may not necessarily have to be uniform. However, the optimum profile will be required to be determined such that adequate consolidation levels are achieved.

The equipment can be configured in such a way as to increase the throughput rate through a multi-head scenario. The feasibility of this concept is enhanced for simple geometries, such as cylinders. In addition, due to the localized nature of the in-situ consolidation fiber placement process, each head is independent of each other with regards to consolidation of material. However, head dependency will be present with regards to machine control and motion. Furthermore, loads applied to the tooling by the multiple heads will need to be considered during tool design and machine platform design. For example, opposing heads may be beneficial due to the fact that the loads applied by each head will oppose each other.

If one considers 30,5 cm wide tape that is 0,5 mm thick and is processed with four heads, a scale factor of 738 results over the current processing of 0, 6 cm wide tape that is 0, 12 mm thick with one head. Furthermore, if the feed rate is doubled, the scale factor is increased to 1476. Consequently, the potential exists to achieve throughput rates in the 90 to 180 kg/hr range for a limited class of geometries and marine applications making this fabrication process very economical.

## 4.0 MANUFACTURING ASSESMENT

Prior to producing the 1,22m (48 inch) diameter design validation test article, ICI fabricated a 61 cm (24 inch) diameter laboratory scale cylinder with three framing schemes a blade, "I" stiffener and "T" stiffened blade from APC-2/AS-4 thermoplastic material (Figure 9). The primary purpose of the laboratory scale cylinder was as a manufacturing demonstration and risk reduction article and to demonstrate various thermoplastic process technologies and stiffener concept fabrication while maintaining scale up considerations [4]. These stiffening concepts were also representative of high throughput thermoplastic processing; i.e., thermoforming and stamping. The fabrication article would also demonstrate part integration by in-situ placing material over existing subcomponent assemblies resulting in an integrated assembly. The blade stiffener concept is composed of in-situ circumferential plies. The "I" stiffener includes quasi-isotropic webs and flanges to provide the necessary lateral load and attachment capabilities. Inner and outer hoop flange caps are also included to provide the required continuous hoop strength. This fabrication technique permitted the percentages of quasi-isotropic and hoop plies to be optimized for the maximum performance and minimum weight.

The "I" frame stiffeners are formed from 90° segments of quasi-isotropic stamped channel sections which are placed back to back with a 45° segment overlap and co-consolidated in an integrally heated tool with an all hoop inner ring flange which is in-situ consolidated. The consolidated "I" frames are then placed in a segmented tool and overwrapped with an all hoop outer flange cap using in-situ consolidation. The stiffened cylinder is then completed by overwrapping all of the stiffeners in the segment mandrel with the hull lay-up. After all the hull plies have been placed, the core mandrel is extracted and the segmented mandrel is disassembled and removed.

In addition to the 61 cm diameter fabrication demonstration laboratory model, GD/ICI/ADC produced three blade stiffened 61 cm diameter submersible test models using AS4C/APC-2A material and one with AS4/PPS. One of these is shown in Figure 10.

To mitigate risk and determine processing parameters for the 1,22m (48 inch) diameter subscale cylinder, a manufacturing demonstration article with one "I" stiffener frame was fabricated. The tooling concept used in the manufacture of the 61 cm diameter subscale cylinder was scaled up to 1,22m. The "I" stiffener was fabricated as discussed earlier. Figure 11 shows the completed frame assembly prior to being positioned on the core mandrel. The stiffener was held in alignment by the segmented tooling. The cylinder overwraps were in-situ consolidated directly over the stiffener assembly using AS4/APC-2, 2,54 cm slit tape for the required hull layup (Figure 12). The completed manufacturing demonstration article is shown in Figure 13. ADC is currently fabricating AS4/PPS "I"-stiffener assemblies using lessons learned from the fab demo article. These will then be assembled in a tool and the hull overwraped by in-situ consolidation as discussed above. The model will be hydrostatically tested to assess fabrication performance and design predictions.

## 5.0 SUMMARY

Composite materials for marine structures offer the potential benefits of reduced weight and maintenance, improved stealth and survivability over existing metal structures. However, the high fabrication costs associated with advanced composites have to be reduced while maintaining quality to be competitive. Advances in the in-situ consolidation fiber placement process have been addressed in this paper leading to lower cost, higher quality, scaleable, automated fabrication process for thermoplastics. Several process related cost factors have been addressed to include throughput, scaleability and part integration which contribute to reducing manufacturing costs. Enhancements in placement rates, material forms (widths and thickness) and equipment configurations (multi-head approaches) have contributed to increasing the throughput for thermoplastic fiber placement technology. However, the level of porosity permitted and cost will depend on the end use whether commercial or military. Improvements in thermoplastic fiber placement process will continue through the manufacture of ARPA validation articles. The design, fabrication and testing of the 1,22 m (48 inch) diameter marine validation ARPA models will establish a high level of confidence before progressing to the full scale Composite Dry Deck Shelter and form a sound basis for affordable thermoplastic fabrication of marine structures.

## 6.0 ACKNOWLEDGEMENTS

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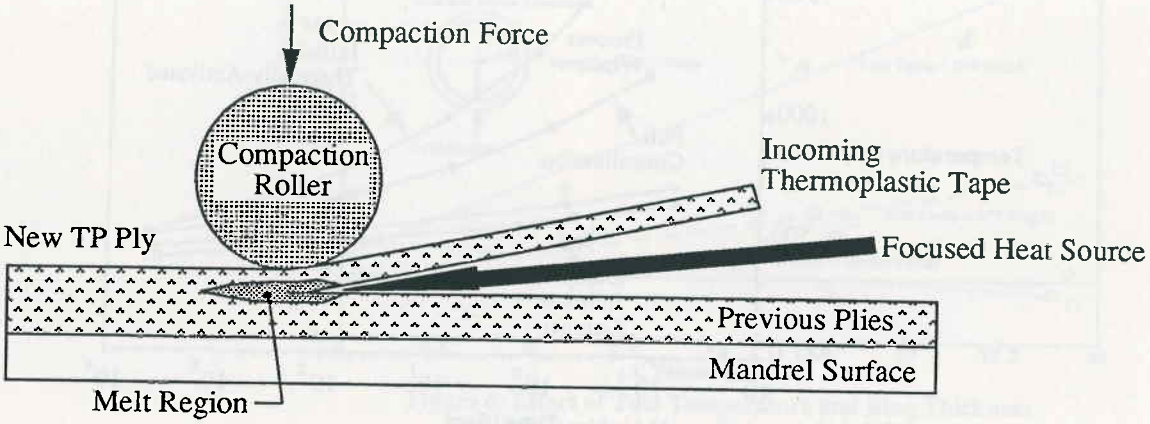

Figure 1 - In-Situ Consolidation Fiber Placement Process Schematic

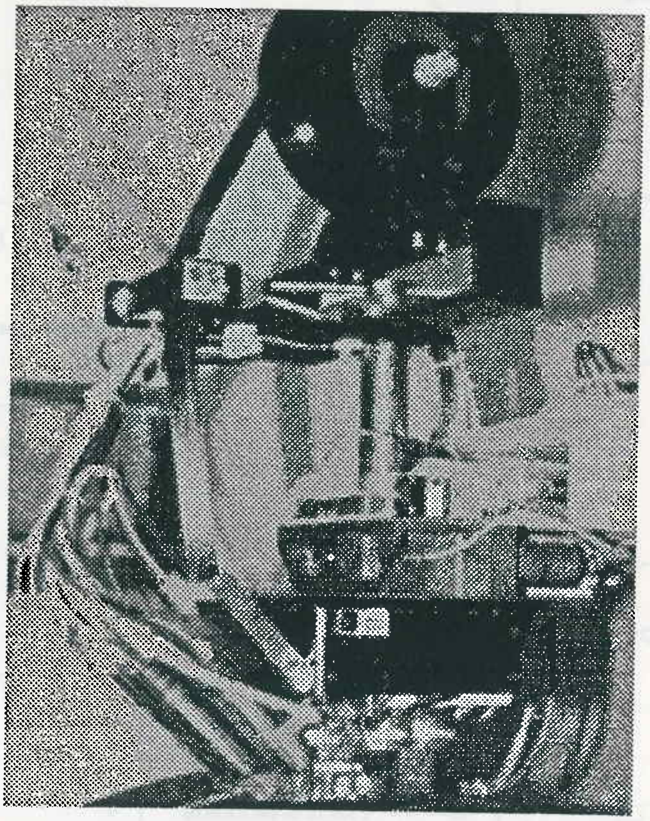

Figure 2 - ADC 5 Hot Gas Torch Head

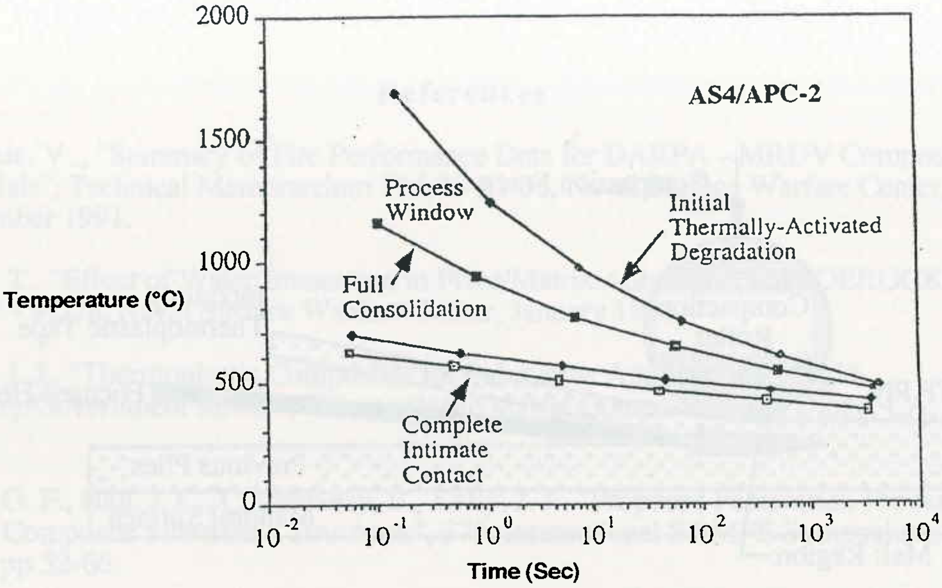

**Fig. 3** Temperature History for Specific Fabrication Sequence

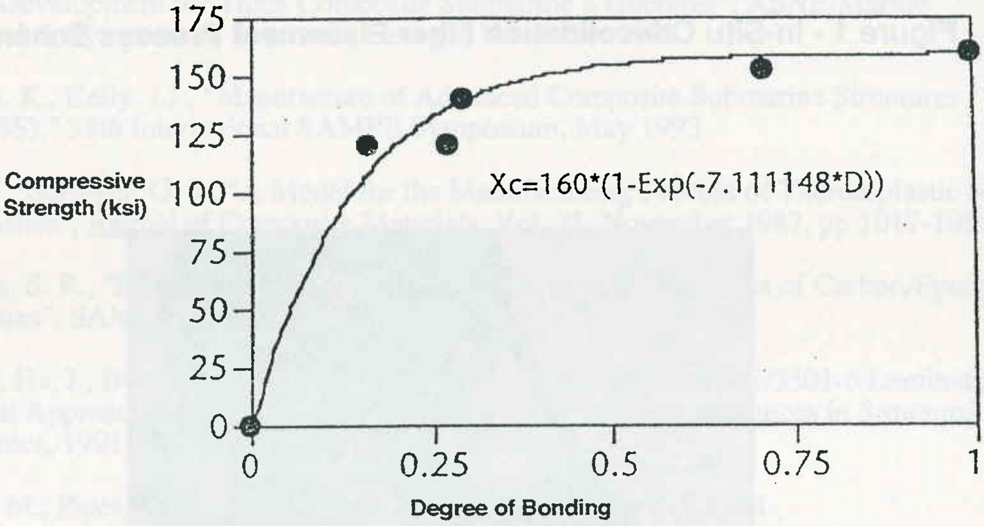

**Fig. 4** Empirical Relationship Between Degree of Bonding and Compression Strength

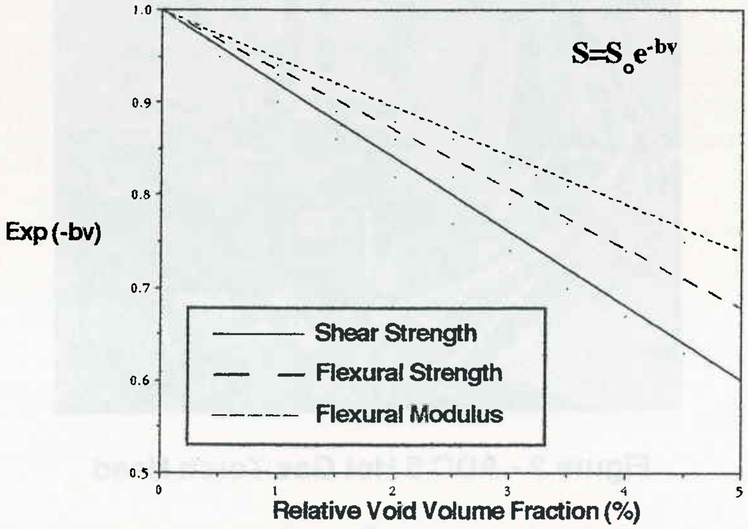

**Fig. 5** Exponential Curve Fits vs. Void Content for Carbon/Epoxy in a $[0/90]_{4s}$ Layup

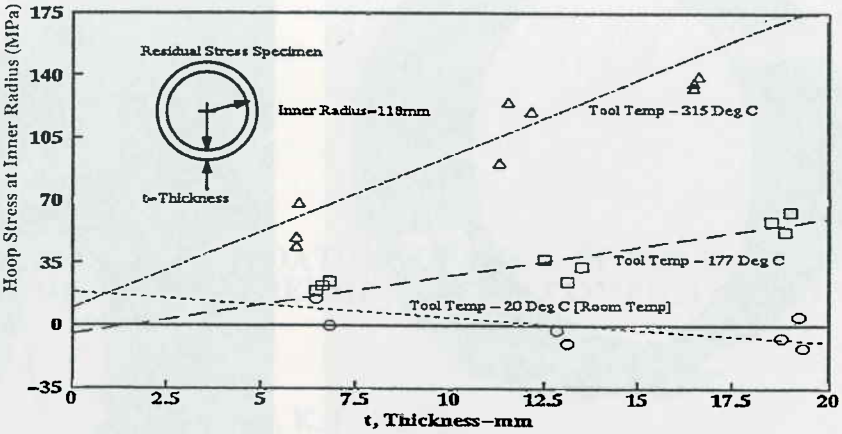

Figure 6: Effect of Tool Temperature and Ring Thickness on Residual Hoop Stress. AS4/APC-2

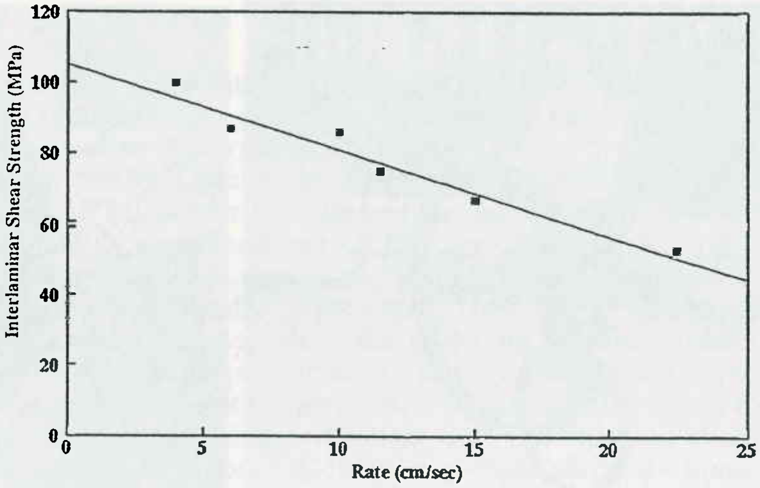

Figure 7: Interlaminar Shear Strength vs. Rate for AS4/APC-2 In–Situ Consolidated NOL Rings

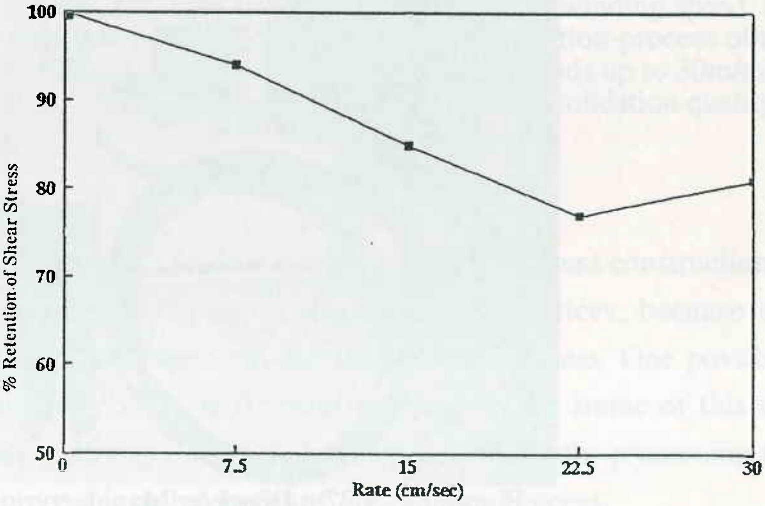

Figure 8: Throughput Versus Performance for AS4/PPS

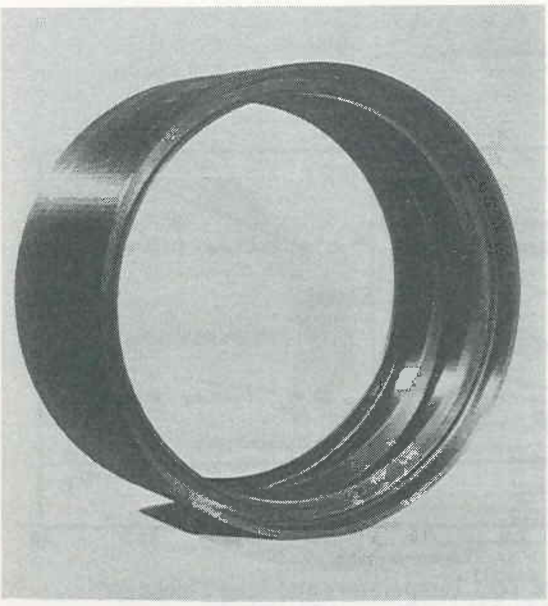

Figure 9 - Three Frame AS4/APC-2 Cylinder

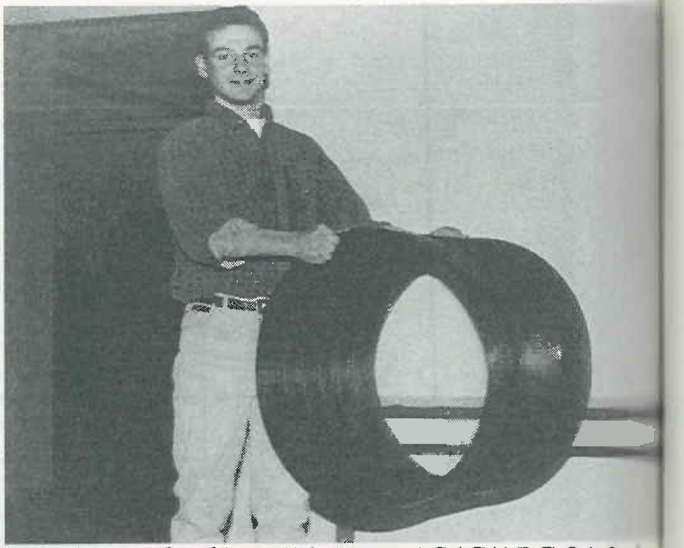

Figure 10 - 61 cm Diameter AS4C/APC-2A Lab Model

Figure 11 - Stamped, Co-Consolidated, 1,22m Dia. and 61 cm Dia. AS4/APC-2 Stiffeners

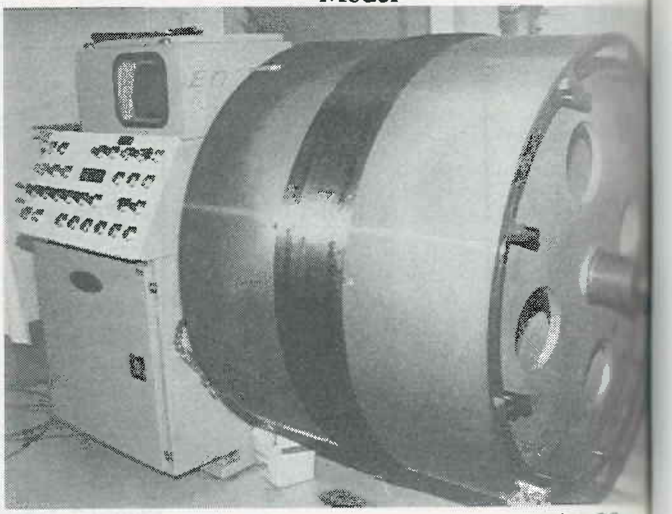

Figure 12 - Thermoplastic Overwrap of 1,22m Diameter Stiffener and Shell

Figure 13 - 1,22m Diameter Manufacturing Demo