N92-22678

RTM: COST-EFFECTIVE PROCESSING OF COMPOSITE STRUCTURES

Greg Hasko
Materials Research Engineer
Lockheed Engineering & Sciences Co.
Langley Program Office
144 Research Drive
Hampton, VA 23666
(804) 864-3093

H. Benson Dexter
Materials Research Engineer
NASA Langley Research Center
Mail Stop 188B
Hampton, VA 23665-5225
(804) 864-3094

ABSTRACT

Resin transfer molding (RTM) is a promising method for cost-effective fabrication of high-strength, low-weight composite structures from textile preforms. In this process, dry fibers are placed in a mold, resin is introduced either by vacuum infusion or pressure, and the part is cured. RTM has been used in many industries, including automotive, recreation, and aerospace. Each of the industries has different requirements of material strength, weight, reliability, environmental resistance, cost, and production rate. These requirements drive the selection of fibers and resin, fiber volume fractions, fiber orientations, mold design, and processing equipment. NASA Langley is sponsoring research to apply RTM to primary aircraft structures such as wings and fuselages, which require high strength and stiffness at low density, and are produced in relatively small quantities. However, there is a continuing need to reduce the cost of fabricating advanced composite structures.

This paper discusses the material requirements of various industries, methods of orienting and distributing fibers, mold configurations, and processing parameters. Processing and material parameters such as resin viscosity, preform compaction and permeability, and tool design concepts are discussed. Experimental methods to measure preform compaction and permeability are presented. Analytical methods that predict resin infiltration and cure are discussed. Mechanical properties and potential applications of selected textile material forms are also mentioned.

INTRODUCTION

Resin transfer molding (RTM) is a method of combining dry fibrous preforms with matrix resins in a mold to yield structural components. It has been used for making products over the last few decades in several industries. Parts are made with this process that often require little or no machining. The important relationships between end user (customer) requirements and component design and fabrication are depicted schematically in figure 1. There are significant differences in constituent materials and process parameters, depending on factors shown in figure 1. Overall selection of constituent materials is driven by the customer's performance needs, production volume, and cost sensitivity. Specific performance criteria are then defined and the design engineer can bracket the material selections. The type of fiber, its volume fraction, and orientation are selected by considerations of strength, stiffness, weight, and cost. Selection of resin is guided by service environment, lifetime requirements, reliability, and cost of the final part. The process engineer specifies temperature and pressure cycles and the equipment used to control them in order to produce repeatable parts within the allowable material processing windows. This paper discusses aterial and process selection for RTM, and analytical methods that help ensure cost-effective product development and production.

MATERIAL AND PROCESS SELECTION

Material Properties

Composite materials offer a wide range of material properties. This is illustrated in figure 2, which shows approximate specific strengths and stiffnesses of fiber composites and metals [1]. In comparison with composite materials, typical engineering metals have very narrow strength and stiffness ranges. Fiber composites have a considerably greater envelope in both strength and stiffness. Because of large differences in properties for fibers and resins, properties of composites can vary by a factor of 10 or more.

Composites allow tailoring of properties to the directions of applied loads, as shown in figure 3 [2, 3]. For a beam requiring stiffness in only one direction, a unidirectional graphite fiber reinforcement would be the stiffest and lightest. Skin panels of typical automotive or aerospace vehicles usually require uniform properties in all directions, so a multi-angle graphite laminate or a randomly oriented chopped glass composition should be considered. Aircraft wing skins are made of multidirectional graphite laminates, whereas automotive exterior panels use chopped glass molding compounds. Chopped glass is less structurally efficient, but less expensive than continuous graphite fiber reinforced composites because of lower fiber cost and simpler fiber deposition method.

The environmental performance of composite materials is strongly influenced by the nature of the resin. As shown in figure 4, polyester resin composites can lose 50 percent of their room temperature strength at 250°F. Epoxy resins can lose this same amount by 300°F, and bismaleimide resins by about 450°F [2, 3].

The weak link in a laminated composite is the interface between layers. Impacts from dropped tools or other items can cause delamination. Damage resistance of a composite is influenced by both fiber and resin selection. Figure 5 shows how strength retention after impact is increased by knitting and stitching the layers of reinforcement together and by using a toughened resin [4, 5]. In general, higher performance resins are more expensive and more difficult to process.

Cost Issues

Figure 6 shows the cost trends of currently used composite materials. Metals and low fiber volume glass composites used in the automotive industry are under $2 a pound [2]. There is a much broader range of high-performance fiber and resin costs, typically over $20 a pound for aerospace applications. Depending on stiffness and toughness requirements, the fiber or the resin may be the more expensive constituent. Cost is also process dependent: for RTM processing, the reinforcement and the resin are procured as separate components, which generally is the lowest cost form. For autoclave processing from prepreg tape, these constituents must first be combined by a prepregger prior to procurement by the part fabricator, adding another processing step and cost. More critical structures require greater control of fiber content and orientation, which adds cost.

Selection of processing methods to arrive at a given composition and orientation is guided by the cost of equipment and the volume of parts to be produced. Several thousand units of a given automobile frame are made yearly, whereas aircraft production may be as few as one hundred over several years. In automobile companies, production is based on market projections, whereas large aircraft manufacturers typically build only what is ordered. Trends of equipment cost amortized over production volume are shown in figure 7. Automotive composites manufacturers must invest in sufficient production capacity to meet assembly line rates. Aircraft companies, having lower production rates, require a lower investment. However, limited production volume can still cause high amortized unit costs.

Composite Processing Variations

For a given fiber content and orientation, many processes are available to fabricate the part. Originally, composites were mostly made by hand, laying down sheets of material or spraying chopped fibers on a mold. The laydown and spraying processes have been automated for greater control and efficiency. Continuous methods such as winding over a mandrel or pulling through a die are used. These methods place limits on the fiber orientation, especially if through-thickness reinforcement is desired. NASA is putting emphasis on textile methods to orient large quantities of fiber by rapid, automated processes. These methods include weaving and braiding of net shape structural elements with through-thickness fibers, as shown in figure 8.

An important cost factor in composite fabrication is how the matrix resin is introduced. One way is to apply resin before storing the raw material on a roll, as in prepreg. In order to prevent the resin from curing on the roll, it must be refrigerated. In pultrusion and filament winding, resin may be applied just before contact with the forming surface. Some resins are so viscous that fiber distortion or air entrapment are difficult to eliminate. With prepregs, it is impractical to introduce through-thickness fibers for damage tolerance, whereas RTM methods can allow processing for a wider variety of reinforcements and resins.

RESIN TRANSFER MOLDING

In usual RTM practice, dry fibers are oriented in a mold and resin is introduced from a reservoir. The reservoir may be in intimate contact with the perform or located several feet away in a heated tank connected by a heated hose to the mold. Resin flow direction can be through the thickness or in the plane of the preform. The type of mold depends on the compaction needed to obtain the final fiber volume fraction and on temperature requirements of the resin. Examples of these variations follow.

Tooling

Figure 9 shows a patented process in which flow into the mold occurs in three steps: from one inlet to a lengthwise conduit, then laterally across the surface area, then through the thickness of the preform [6]. A single-sided hard mold is used, with the other side consisting of layers of porous materials and a vacuum bag. Figure 10 shows a similar through-the-thickness flow in the preform, but the reservoir consists of a solid film of resin placed in the mold. The resin melts and flows into the preform under heat and pressure. The compaction pressure is also the resin infiltration pressure. Figure 11 shows the same process as figure 10 applied to a typical aircraft wing skin with stiffening members attached to the skin [7]. Heat and pressure are applied with an autoclave.

Figure 12 is a typical pressure injection mold with an external reservoir. The preform compaction pressure is applied independently of resin injection pressure. Figure 13 is a patented version of an in-plane pressure injection process for forming hollow parts. The inside surface is defined by a pressurized bladder [8].

Mathematical Process Models

Process parameters for a specific part have historically been based on experience. Mold design, heating method, flow path, and time/temperature/pressure cycles were determined by past experience and "build and break" trials. NASA Langley has been sponsoring research on reducing the need for a trial-and-error approach by applying a science-based understanding of the process. Success of the science-based approach depends on accurate data for the preform and resin processing behavior, and on mathematical models of the process.

The flow of resins through fiber performs can be modeled in a similar manner as the flow of a fluid through any porous media. Darcy's Law states that the flow rate (Q) is directly proportional to the pressure gradient $\Delta P/X$, area (A), and permeability (K); and inversely proportional to viscosity (μ):

$$Q=\left(\frac{K}{\mu}\right)\frac{\Delta P}{X}A \qquad (1)$$

The permeability of a preform is dependent on the fiber size, weave geometry, packing density, and direction of flow. The viscosity of the resin is dependent on its entire time/temperature history. These parameters can be measured and modeled in order to predict flow rate and pressure for any type of preform and any cure cycle. Currently, the preform and resin manufacturers do not supply the data needed to successfully model the RTM process. NASA Langley is supporting development of material characterization methods and process models.

Preform Compaction and Permeability

Preform compaction behavior, needed for input into process models, is measured in a fixture where a known compaction pressure is applied to a sample and the thickness is measured, figure 14. Fiber volume fraction is directly proportional to thickness but is indirectly related to compaction pressure. As shown in the figure, preforms in an ambient, uncompacted state range from 30 to 52 percent fiber volume. Vacuum bag pressure (14.7 psia) shifts this range to 35 to 55 percent. For automotive and recreational products, these values may be acceptable. However, high-performance aerospace components require high stiffness to weight ratios. Material selection is driven towards graphite composites of 60 percent fiber volume, which require 30 to 130 psi for proper compaction.

Permeability information for a preform is determined by compacting a sample of the material to a known fiber volume and pumping a fluid of known viscosity, figure 15. Flow rate and pressure drop are recorded and permeability is calculated using equation (1). This test is done at varying fiber volumes and in the three primary preform directions. Permeability has been found to vary by a factor of 100 when measured along and across a fiber bundle. Resin can flow much easier along a bundle than across it. In addition, as shown in figure 15, permeability can vary by a factor of 100,000 between a glass mat at 25 percent fiber volume and woven graphite at 70 percent fiber volume [9, 10, 11].

Resin Viscosity Behavior

Resin viscosity can vary by several orders of magnitude, depending on its chemistry, aging history, and temperature. Figure 16 shows viscosity behavior for three different epoxies (Hercules 3501-6, British Petroleum E905L, and 3M PR500), each at two selected temperatures.[1] In general, higher processing temperatures reduce the initial viscosity but cause the viscosity to increase at a faster rate as cure progresses. For small parts or high permeability preforms, a higher temperature will allow quick wet out. However, with large parts or low permeability preforms, the resin may gel prior to full impregnation if the mold is designed for in-plane flow. Success may be achieved with a through-thickness flow path.

Figure 17 shows an example of the processing window for a hot melt epoxy. This material melts as the mold heats up, reaches a minimum viscosity, then reacts and thickens. All of the flow into the preform must occur before the viscosity starts to increase.

Versatility of Textile Equipment

It is possible to produce preforms for both the automotive and aerospace industries using a common textile machine. For example, the braider shown in figure 18 can produce preforms for automobile bodies or for jet engine inlets. To successfully complete the process development cycle, both industries would benefit from a mathematical model of the RTM process to aid in mold design and process control.

RTM Computer Model

Under a NASA grant, Virginia Polytechnic Institute and State University has been developing the computerized model of the RTM process shown schematically in figure 19. Currently, the model simulates only one-dimensional flow occuring in a through-thickness process. The user selects mold design and process parameters, and the program calculates the variation in compaction, permeability, heat transfer, cure kinetics, and resin flow with time. The program calls on subroutines for specific preform and resin characteristics. With sufficient data, the program accurately models the behavior of the preform and resin inside the mold up to final cure of the part. The model is being extended to include two- and three- dimensional flow conditions. Computing requirements for the model are also shown in figure 19. Model predictions have been verified for several one-dimensional cases by fabricating panels in instrumented molds.

[1] The use of trademarks of names of manufacturers in this paper does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

RTM Flow Sensing and Control

The College of William and Mary has developed a sensor system under a NASA grant to monitor resin parameters during composite processing. Termed Frequency-Dependent Electromagnetic Sensors (FDEMS), a single sensor can monitor the degree of wet out, viscosity, and cure state of a resin. Several sensors can be placed in an RTM mold to monitor many locations at once. An additional benefit of such a monitoring system is that sensor output can be used to control the process in real time, based on actual resin parameters, as opposed to indirect parameters such as mold surface temperature. This system can be used during process development or in production to control mold temperature, as shown in figure 20.

CONCLUSIONS

Composite materials offer the designer a wider range of properties and higher performance than metals. However, raw material and processing costs of composites are a barrier to their greater utilization in industry. The key to greater acceptance of composites lies in process innovations that result in a cost-effective product.

RTM processing allows fabrication of composite materials into components of complex shape with any desired fiber orientation and all but the most viscous resins. However, mold designs and process parameters can vary tremendously. Analytical tools are needed to identify the key variables leading to a cost-effective product and process. NASA's efforts in science-based understanding of RTM can guide mold design and process development and help control process variables in production. The same approach can be useful in an industrial environment, ranging from the automotive body panel made from chopped glass and polyester resin in an in-plane mold at room temperature, to an aircraft wing skin made of woven, stitched graphite and hot melt epoxy in a through-thickness process. In conjunction with near- net shape textile preforms, RTM shows great promise to be a cost-effective process for producing high-quality composite structures.

References

1. Jones, R. M: Mechanics of Composite Materials. Scripta Book Co., 1975, pp. 92.

2. Engineered Materials Handbook Volume 1 - Composites. ASM International, 1987, pp. 220, 379, 395, 411.

3. DOD/NASA Advanced Composites Design Guide. p.4.1.1, July 1987.

4. Dexter, H. B.; Hasko, G. H.; and Cano, R. J.: Characterization of Multiaxial Warp Knit Composites. Presented at the First NASA Advanced Composites Technology Conference, NASA CP-3104, 1990.

5. Dow, M. B.; and Smith, D. L.: Properties of Two Composite Materials Made of Toughened Epoxy Resin and High-Strain Graphite Fiber. NASA TP-2826, July 1988.

6. Seeman, W. H.: U.S. Patent #4,902,215.

7. Markus, A.; and Palmer, R.: Resin Transfer Molding for Advanced Composite Primary Structures. Presented at the First NASA Advanced Composites Technology Conference, NASA CP-3104, 1990.

8. Freeman, R. B.: U.S. Patent #4,911,876.

9. Kim, Y. R., et. al.: Resin Flow Through Fiber Reinforcements During Composite Processing. 22nd International SAMPE Technical Conference, November 1990.

10. Trevino, L., et. al.: Analysis of Resin Injection Molding in Molds with Preplaced Fiber Mats. 1: Permeability and Compressibility Measurements. Polymer Composites, Vol. 12, No. 1, February 1991.

11. Gutowski, T. G., et. al.: Consolidation Experiments for Laminated Composites. Journal of Composite Materials, July 1987.

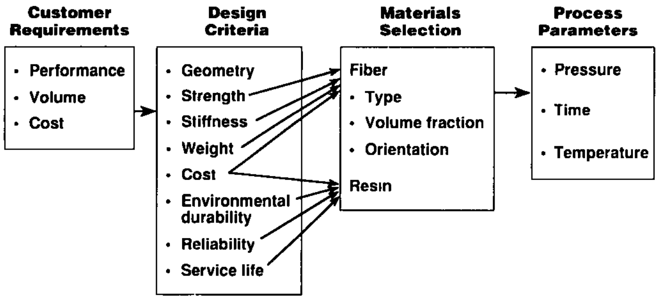


Figure 1. Material and Process Drivers

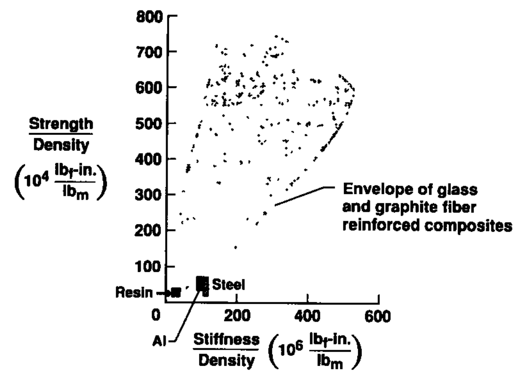


Figure 2. Specific Strength and Stiffness Advantages of Composite Materials

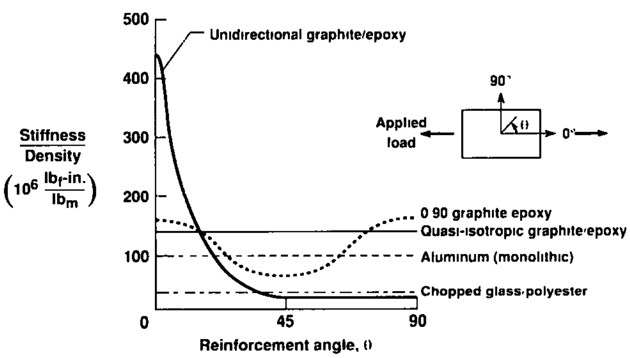


Figure 3. Specific Stiffness as a Function of Reinforcement Orientation

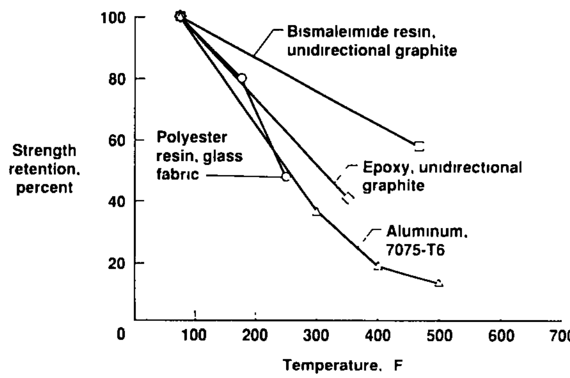


Figure 4. Effect of Temperature on Strength Retention of Materials

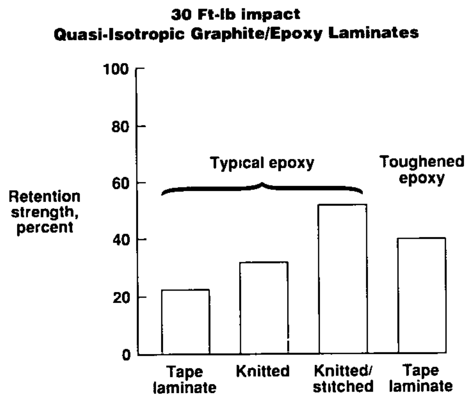


Figure 5. Compression after Impact Strength

Processing and Scrap Costs Omitted

Material	Cost, $/lb	End use
Steel	0.38	Automotive
Aluminum	1 44	Automotive
Glass-filled thermoplastic	1.70	Automotive; Recreation
Low performance graphite/epoxy (sum of constituents for RTM processing)	17.00	Recreation
High performance graphite/epoxy (sum of constituents for RTM processing)	33.0	Aerospace
High performance graphite/epoxy (prepreg cost)	40.00	Aerospace

Figure 6. Raw Material Cost Comparison

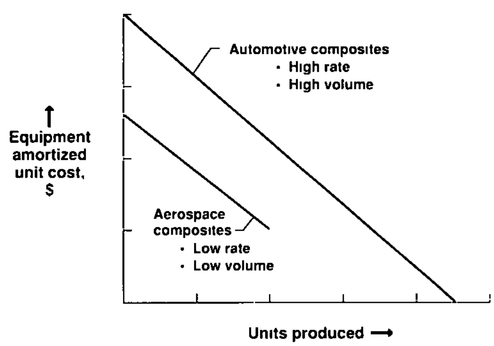


Figure 7. Relative Amortized Equipment Cost Per Unit Produced

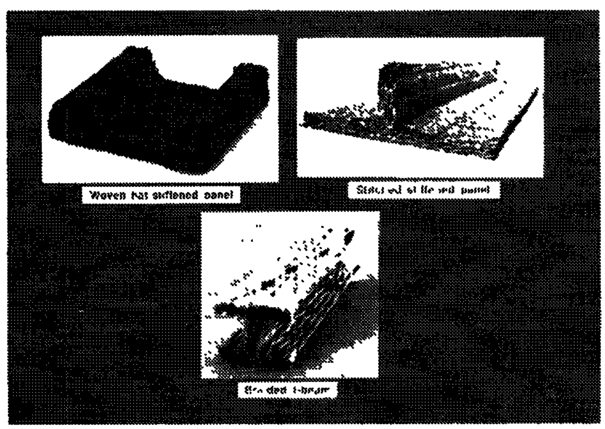


Figure 8. Net-Shaped Fiber Preforms

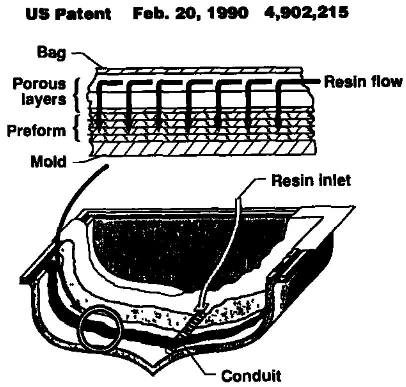


Figure 9. Liquid RTM, Bag Mold, Through-The-Thickness Flow

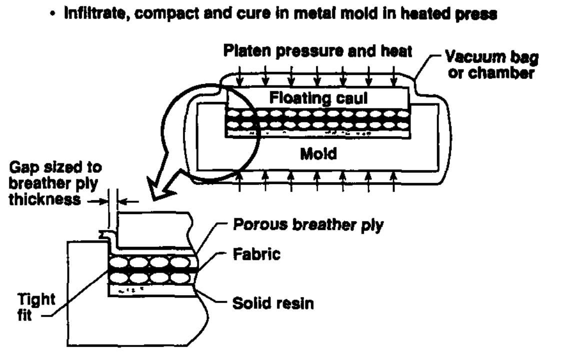


Figure 10. One-Step Through Thickness Vacuum/Pressure Process

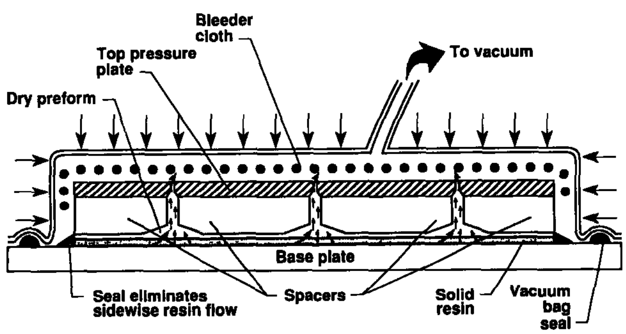


Figure 11. Resin Film Infusion of Stiffened Panel

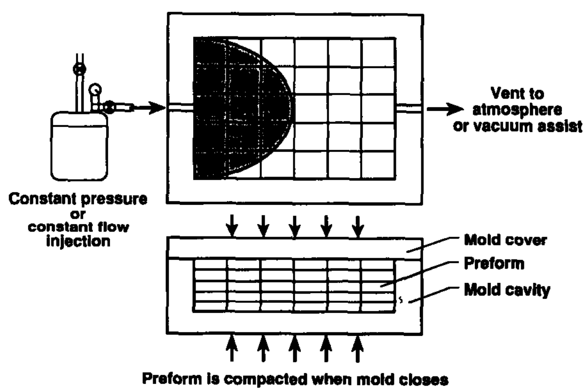


Figure 12. Pressure Injection

US Patent March 27, 1990 4,911,876

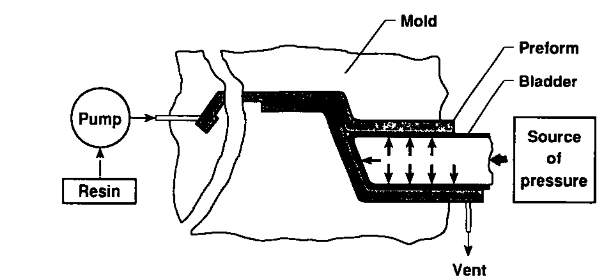


Figure 13. Liquid RTM, Inflatable Bag Mold, In-Plane Flow

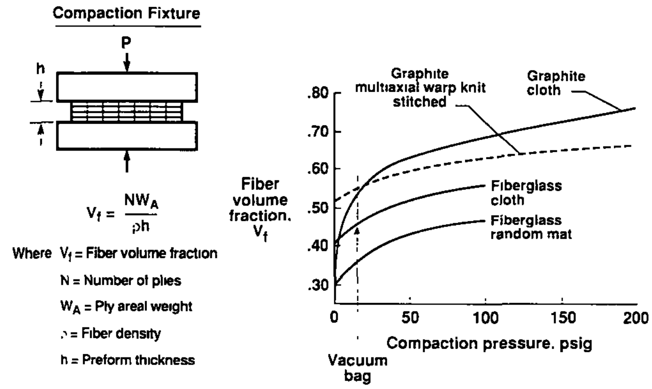


Figure 14. Preform Compaction Behavior

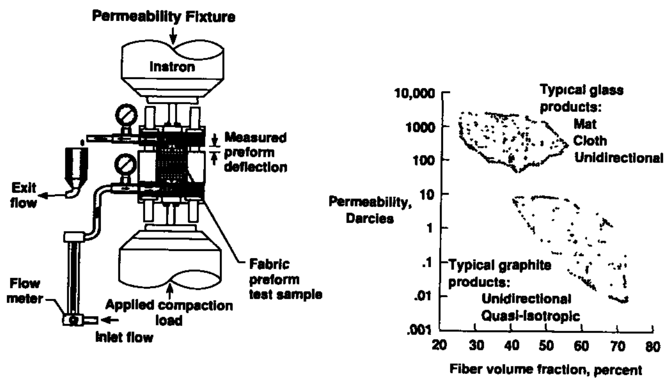


Figure 15. Permeability Comparison

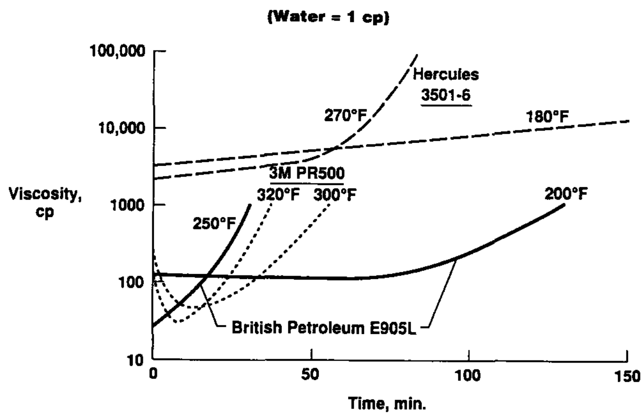


Figure 16. Effect of Time and Temperature on Viscosity of Epoxy Resins

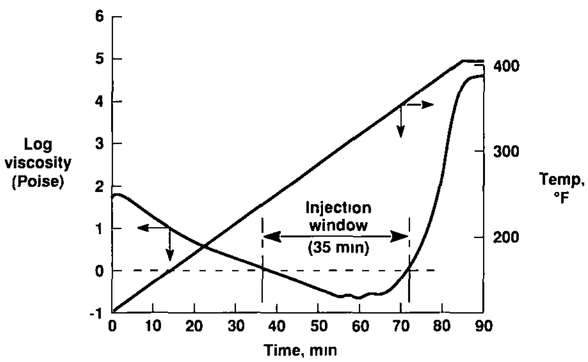


Figure 17. Viscosity Profile for PR500 Epoxy

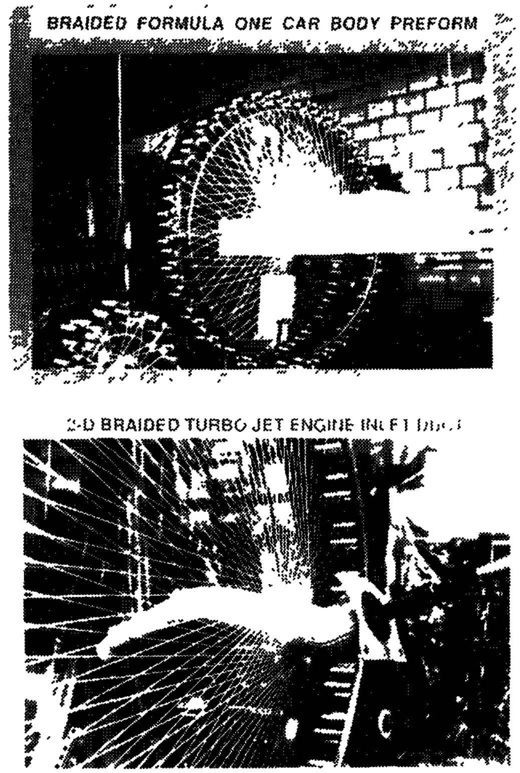
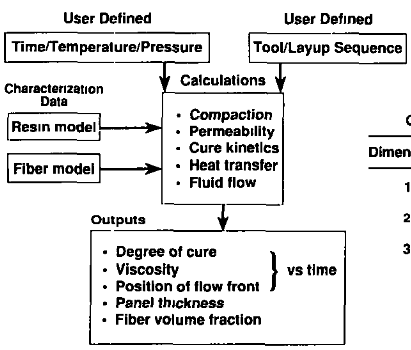


Figure 18. Braiding Preforms for Automotive and Aerospace Use



Computing Requirements

Dimensions	Computer	Run time
1	PC	30 min.
2	Mainframe	3 hr
3	Cray	?

Figure 19. RTM Computer Model

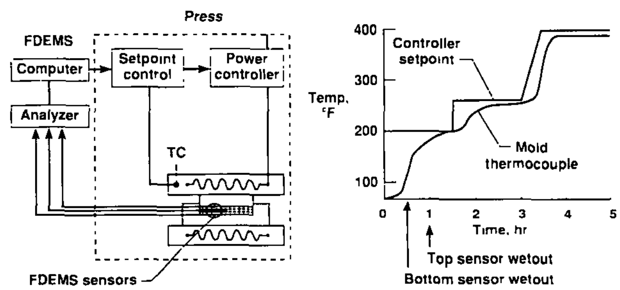


Figure 20. Prototype FDEMS Expert Cure System