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Composite Fabrication via Resin Transfer Molding Technology

G. M. Jamison, L. A. Domeier

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COMPOSITE FABRICATION VIA RESIN TRANSFER MOLDING TECHNOLOGY

An IMPReS Program Summary

G. M. Jamison
Properties of Organic Materials Department
Sandia National Laboratories/New Mexico
and
L. A. Domeier
Polymer and Electro-Chemical Technologies Department
Sandia National Laboratories/California

ABSTRACT

The IMPReS (Integrated Modeling and Processing of Resin-based Structures) Program was funded in FY 95 to consolidate, evaluate and enhance Sandia's capabilities in the design and fabrication of composite structures. A key driver of this and related programs was the need for more agile product development processes and for model based design and fabrication tools across all of Sandia's material technologies. A team of polymer, composite and modeling personnel was assembled to benchmark Sandia's existing expertise in this area relative to industrial and academic programs and to initiate the tasks required to meet Sandia's future needs. RTM (Resin Transfer Molding) was selected as the focus composite fabrication technology due to its versatility and growing use in industry. Modeling efforts focused on the prediction of composite mechanical properties and failure/damage mechanisms and also on the uncured resin flow processes typical of RTM. Appropriate molds and test composites were fabricated and model validation studies begun.

This report summarizes and archives the modeling and fabrication studies carried out under IMPReS and evaluates the status of composite technology within Sandia. It should provide a complete and convenient baseline for future composite technology efforts within Sandia.

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COMPOSITE FABRICATION VIA RESIN TRANSFER MOLDING TECHNOLOGY

Introduction

This report summarizes the experimental and computer modeling results of a team of individuals working under the IMPReS (Integrated Modeling and Processing of Resin-based Structures) program. The goal of that program was to begin providing a comprehensive capability within Sandia for the agile design and production of fiber reinforced composite structures. While funding was obtained for only one of the three years planned, significant progress was made which both enhanced and clarified Sandia's expertise in these areas.

The IMPReS program was initiated in FY 95 to add the "smart" design and manufacturing of polymeric materials to the suite of similar emerging smart material processing programs within Sandia. The need to provide more rapid and reliable part fabrication technologies has been the driver behind this and related metal fabrication programs such as FASTCAST and SMARTWELD. These model/knowledge based tools are expected to be available to component designers as they seek to realize finished parts with greatly reduced cycle times relative to a traditional and time consuming regimen of "design → fabrication → test → re-design".

With total first year funding of \$700K from the DP-directed Enabling Processes program, IMPReS coordinated a multi-disciplinary effort in the fabrication, testing, process flow modeling, and mechanical property and composite failure modeling of components fabricated by RTM (Resin Transfer Molding). The intent was to begin the evaluation, refinement and implementation of model based design and processing tools for use in future DP composite applications.

Resin Transfer Molding (RTM) is a composite fabrication technology whereby net or near-net shape parts of relatively complex geometry with high ($\leq 60\%$) carbon, glass or synthetic fiber reinforcement loadings can be made. An appropriate fiber preform (woven, sprayed or layered) is placed within a mold followed by injection of a liquid resin to infiltrate the preform and fill the mold. The assembly is then cured at the required time and temperature schedule and demolded. Equipment for this process is in place at Sandia/CA. Advantages of RTM over other molding processes and over prepreg hand lay-up include the ability to fabricate more complex shapes, part consolidation, low personnel exposure to toxic resin components, relatively low injection pressures, and the potential for process automation (preform insertion, resin injection, part removal after cure).

RTM is becoming the favored method for fabricating many reinforced parts in the automotive and aerospace industries. Industrial participants at recent NIST workshops also

identified RTM as the composite technology most strategically important to national security and economic competitiveness.

Industrial interest in RTM is strong and extends to research programs in academia (i.e. the Center for Composite Materials at the University of Delaware, composite research at Michigan State University, Florida State University, Cerritos College, and the Design and Manufacturing Institute at the Stevens Institute of Technology). Most of these programs, like the Sandia IMPReS program, are concerned with the development and implementation of validated design and process tools which can reduce costs, improve development cycle times and increase final part reliability.

Program Outline

As noted above, the components of the IMPReS program specifically included:

1. Flow Models. Modeling of resin flow front behavior utilizing various commercial and Sandia-based computer codes and an evaluation of the strengths and weaknesses of those codes.

2. Composite Performance Models. Modeling predictions of fabric preform micromechanical structures and properties, cured composite mechanical properties, and failure mechanisms including evaluations of the state of the art in commercial and academic codes.

3. RTM Processing Infrastructure. RTM equipment, molds and materials acquisition and demonstrations of component fabrication.

4. Model Validation Experiments. Mechanical property test data on flat panel parts with different reinforcements and photographic evaluation of fill patterns using molds with windows.

5. Sandia Composite Capabilities. A critical evaluation of Sandia capabilities relative to identified academic/industrial concerns known to have expertise in the area of concurrent engineering of fiber-reinforced composites.

Program accomplishments in the above areas are briefly summarized below and are detailed in the attached appendices.

Team Personnel

Tom Bennett	CA	composite fabrication
Steve Burchett	NM	coordination of modeling efforts
Jim Costa	CA	program initiation and management
Linda Domeier	CA	program management and resin selection
Tommy Guess	NM	composite testing
Greg Jamison	NM	program management and resin selection
Rekha Rao	NM	flow modeling
Cliff Renschler	NM	program initiation and planning
Ann Marie Sastry	NM	composite performance modeling

John Sayre	NM	program initiation and planning
Jill Schwegel	CA	flow modeling
Jay Spingarn	CA	composite fabrication
Khanh Trinh	CA	composite performance modeling

Midway through the program Ann Marie Sastry left Sandia for a faculty position at the University of Michigan. She continued her portion of the program under contract there.

Initial Program Definition (details in Appendix A)

Many of the drivers and constraints which defined IMPReS were developed by a small group of managers and technical staff during the start-up phase of the program. A series of view graphs collected in Appendix A summarize those criteria and also the initial set of expected deliverables. Those deliverables evolved during the course of the FY95 program as the tasks and the scope of the effort became more focused and more technically specific.

Flow and Performance Model Overview (details in Appendix B)

RTM composite fabrication, like many polymer fabrication processes, is a complex blend of many simultaneous flow, heat transfer and cure processes. Issues such as reinforcement selection, fiber treatments and wetting, void formation, proper mold design for resin injection and venting, resin selection and rheology, cure conditions, and others all require knowledgeable consideration if the final component is to have the desired performance. An overview (see Appendix B) of the multiple modeling issues and interactions which would need to be addressed was assembled by Steve Burchett. Some of the models required for complete characterization of the composite fabrication process and prediction of the final composite mechanical performance have been or are being addressed by other Sandia programs.

Three areas were selected for modeling evaluation within the IMPReS program:

- flow modeling of a resin front into a mold
- mechanical performance modeling
- failure modeling

Flow Model Evaluation (details in Appendix C)

Four flow modeling codes were evaluated under IMPReS after surveying those available. As yet, neither these or any other codes provide the desired balance of sophistication and ease of use. The codes now used within Sandia, however, may offer the greatest overall potential for meaningful RTM modeling. A summary evaluation is given in the Table below.

Two mold designs were used for the flow modeling and experimental validation efforts. One was a simple flat panel and the other was a box construction with both flat and curved faces. Fixed resin viscosities were used to simplify the model and eliminate the need for heat transfer and cure kinetics in these initial evaluations. The flow front at different fill percentages was to be compared using the chosen models as well as experimental runs. An evaluation of the different code features and formalisms was also made.

Actual fill profiles were obtained from two of the models, ProMOLDESIGN and FIDAP. Both codes gave similar fill patterns in the 2D mode and also agreed well with the experimentally observed fill pattern in a glass-faced mold.

<u>Flow Model</u>	<u>Source</u>	<u>2 vs. 3D</u>	<u>Comments</u>
ProMOLDESIGN	ProEngineer	2D	Simple, especially suited for mold injection port and vent placement design. Can not include reinforcement in model or more sophisticated meshing or other experimental parameters.
C-Mold (C-Set)	AC Technology (Louisville, KY)	2.5D	Complicated resin parameter input requiring vendor pre-processing. Not yet ready for "prime-time!" No flow modeling yet completed due to program deficiencies. Based on Brinkman equations.
FIDAP	Fluid Dynamics International	3D	Modeling carried out on flat panel mesh. Capable of incorporating injection pressure, preform porosity and other features. Based on Forchheimer-Brinkman equations. Probably the most versatile code for further evaluations.
GOMA	Sandia National Labs	2-3D	Only code with the potential to model resin/void interface and formation. No flow modeling yet completed and requires further customizing.

ProMOLDESIGN is a supplement to the ProE system and well suited to evaluating mold designs and the flow of resins through an empty (no reinforcement preform) mold. Adjustable placement of the resin injection and venting ports to minimize air entrapment was readily accommodated by this code. No parameters such as resin viscosity or density or fill time are used.

The C-Set module of C-Mold is designed to handle thermoset polymers (in addition to the thermoplastics covered under the original C-Mold) and was found to be far more preliminary in nature than stated by the vendor. Significant refinements are needed as even inputting simple, constant viscosity thermoset resin parameters was virtually impossible.

FIDAP is a commercial fluid dynamics code which has been modified and which can simulate filling of either empty or preform filled molds. In addition it has the capability of incorporating heat transfer, preform permeability, resin viscosity and cure kinetics, and other features of interest in an RTM process. Both 2D and 3D simulations were carried out and indicated that the lower permeability in the fiber preform in the Z direction would result in different flow characteristics at the front and back mold faces, a feature sometimes noted in actual injections depending on the placement of the injection port. Resin viscosity and preform permeability changes in the model affected the predicted injection pressure, but did not greatly affect the predicted flow path. Simulations were carried out on the flat panel only and used the meshing tools available in FIDAP. The 3D mesh developed for the box mold could not be imported into FIDAP, an unexpected difficulty, and that particular problem is being addressed.

GOMA is probably the most general and sophisticated of the codes evaluated and the only one capable of including the compression and flow of air during the RTM filling process. This might improve the ability to predict trapped air and void inclusions in the final product. A code error at the time of these modeling evaluations prevented the use of GOMA. That problem has since been eliminated and some preliminary GOMA calculations have been carried out. The 2-D results looked very similar to those from FIDAP.

Composite Model Evaluation - Mechanical Performance (details in Appendix D)

A very detailed literature search and evaluation of methods used to model fabric preforms and final composite properties was carried out as reported in Appendix D. While no unified design "tool" exists to optimize preform design and processing parameters (plus resin selection) to provide predictable final composite performance, there exists a great deal of prior art in selected areas, several of which are discussed.

A key feature of the RTM process is the use of fabric preforms, with and without 3D stitching. As such preforms are conformed to fit non-planar shapes such as cones or more complex geometries, there is distortion of the weave and variations in the reinforcement pattern at different points in the composite. Even in a planar conformation, woven fabrics are more constrained and interactive than unidirectional laminates, and begin to exceed the capabilities of simple rule-of-mixture and laminate theory calculations.

Meaningful predictions of the performance of RTM composites will require codes which encompass such fabric preform distortions and which also incorporate weave parameters into more sophisticated laminate and rule-of-mixture based mechanical models. Numerous studies have laid the groundwork in these areas although complete design tools including such features do not as yet exist. A survey of the area identified three major types of analytical models for fabric microstructures (mosaic model, crimp model and bridging model). The distortion of fabrics has

also been simulated, particularly in the draping of a fabric into a cone-shaped preform. Typically there is a compromise between drapability and reinforcement stiffness. Other preform fabrication techniques such as filament winding and layering have also been addressed.

Deformation of the preform and void formation can also occur during the resin injection and flow process. Many facets of this problem such as microporous flow, wetting, wicking, thermal effects, etc. have been experimentally studied. Most models have taken a more simplified approach based on tensor permeabilities.

Final composite performance predictions might also be affected by other factors, some of which are discussed in the appendix.

Composite Model Evaluation - Failure Mechanisms and Micromechanics (details in Appendix E)

Understanding the failure response of a composite structure is generally critical to predicting its suitability for a given application. This performance is usually determined experimentally and modeling tools for such predictions are only beginning to find use in complex composite materials. The development of those tools within Sandia appears to be at the forefront of that technology. The work carried out in this area and described below was only partially supported by IMPReS and was carried out in collaboration with Stanford University. Some of these results have been presented and published in the Proceedings of ICCM-10 (August 1995). That paper and other details are included in Appendix E.

Building on the ABAQUS models already in wide use, two additional material features are being added:

1. criteria to predict the onset of composite material failure

2. degradation rules to simulate progressive damage up to failure

Crack density in the resin matrix is a major parameter in the progressive damage model. Code modifications were required to overcome convergence problems which had previously limited such progressive failure modeling. A wide range of composite failure modes are being accommodated in the model and early predictive studies have been well validated by testing of composite coupons (made at Boeing via hand lay-up and autoclave cure).

In addition to the work on failure mechanisms, a brief survey was made of the micromechanical models of potential use, and perhaps real industrial use, in predicting composite properties. Most such models were found to have limited use in composite structures due to the need for many difficult-to-measure parameters. A simple rule of mixtures often provides adequate ball-park values but tends to lose validity as the fiber volume increases. This approach clearly offers less predictive power than more complicated models which include fabric parameters (examined in more detail in the section above and in Appendix D).

RTM Processing Capabilities at Sandia (details in Appendix F)

Both large and small scale RTM equipment is available at Sandia/California in the IMTL facility.

A semi-production Ashby-Cross 2500 PC-3 RTM machine was acquired from Sutherland & Associates (Sun Valley, CA). This customized equipment is capable of handling two-component resins and features multi-point heat and pressure control, shot size control and programmable process control.

A smaller, one-pot laboratory RTM machine was acquired from RTM Systems, Inc. (Indianapolis, IN) in 1995. This simpler equipment can more easily accommodate resin changes and is suitable for prototyping and preliminary resin and process studies. It is basically a large, pressure operated syringe with a multi-gallon reservoir and attachments for mold evacuation. Similar, quick and small scale experiments have also been carried out using appropriate SEMCO tubes (i.e. pressurized caulking guns) and connectors. Use of such disposable equipment eliminates cleaning operations and allows very rapid process, reinforcement and resin evaluations.

Pictures and brief descriptions of the above equipment are contained in Appendix E.

A survey was also made of commercially available resins for use in RTM. A memo summarizing that information is contained in Appendix F and adequate quantities of the recommended resins were acquired for process and material studies. A different epoxy curing agent recommended by Sutherland & Associates was used in the flow and fabrication experiments to date and is detailed in Appendix G. Two epoxy resins and two urethane resins were also submitted for characterization (with limited results) by AC Technologies, the supplier of the C-Mold software evaluated as one of the flow models.

A growing variety of low viscosity epoxy and urethane resins are available for RTM processing as well as the widely used unsaturated polyester/styrene resins seen in commercial applications such as boats and large household fixtures (such as bath and shower stalls).

Model Validation Experiments - Composite Performance (details in Appendix G)

(Flow model validation experiments are shown in the Flow Model Evaluation appendix. Both flat panels and the more complex box structures were fabricated under a variety of conditions. In the case of the flat panel, a transparent window was included in one face of the mold to allow video tape monitoring of the injection process.)

Large flat panel composites with two reinforcement geometries, one a woven E-glass fabric and the other an A-glass mat with isotropic fiber orientation, were fabricated for mechanical testing. Details of the composite fabrication process and test results are given in Appendix G.

Tensile properties in the fabric composite gave similar results in the $\pm 90^\circ$ axis directions, as expected, and lower values in the 45° off-axis direction. Poisson's ratio in the off-axis direction

was also about three times that observed in the axis directions. Agreement with calculated tensile values using a simple rule-of-mixtures and laminated plate theory approach was reasonable but also indicated that better agreement would require more sophisticated models incorporating details of the fabric construction and also more uniform fiber volumes in the test composites. Some of those more advanced models are discussed Appendix D. Tensile properties in the mat composite were lower overall but more uniform in the axis and off-axis directions as expected. No calculated values from models were available.

General Bibliography (details in Appendix H)

A wide range of articles were acquired during the course of the IMPReS program which are provided as references in Appendix H. Only articles from 1990 on have been included and this is not an exhaustive list. Additional references are provided in the reports in Appendices D and E.

A number of these references address issues such as "smart" manufacturing of composites and indicate the broad activity in this area.

Sandia Composite Capabilities and Conclusions

Results from this one year effort indicate that Sandia has the potential (personnel and resources) to be at the forefront of modeling both the processing and performance of composite materials. Benchmarking evaluations of the available commercial and academic models found none with the full capabilities desired within the composites community. Contacts with industrial users verified this absence of broadly or easily applicable modeling capabilities

Continued composite modeling efforts at Sandia, however, need to be tied to concurrent experimental programs in composite fabrication and model validation. Such an effort needs to be reliably funded and tied to real design and production programs. Justification for such efforts is currently difficult due to a lack of committed and long-term DP component customers.

Collaborative programs with one or more academic or industrial RTM programs might leverage the limited resources within Sandia in the composite area and is recommended as a method to enhance future composite programs. . A variety of contacts during the IMPReS program showed interest in potential academic collaborations with Florida State University, the University of North Carolina at Greensboro, Stevens Institute of Technology and potential industrial collaborations with Eaton Corporation and General Electric. Sandia has previously cooperated with Stanford University in composites research.

Technical expertise in RTM and any other composite technologies requires qualified and experienced personnel and a sustained level of effort. These are not capabilities, either experimental or model based, that can be easily or quickly turned "on and off." They are capabilities which are currently at risk within Sandia.

APPENDIX A—INITIAL PROGRAM DEFINITION

Charts provided by Jim Costa.

IMPRES: A Polymer Paradigm

Integrated
Modeling and
Processing of
Resin-based
Structures

IMPRES: The Project

- Funded by DP, through the Enabling Processes Program
- Program Manager: Duane Lindner, 5605
- Project Manager: Jim Costa, 8711
- FY95 funding level: \$700K
- Expected project life: 3 years

The Scheme of Things

- **The Product Realization MacroProject**
 - Led by Ray Harrigan, 2102
 - Goal: Impact DP production by developing the technologies needed to reduce the life cycle cost and time for small lots of WR products
 - Drivers: Assured reliability and performance
- **Smart Processes**
 - Led by Kim Mahin, 1807
 - Goal: Providing DP designers with ready access to materials data, processing knowledge, and simulation capabilities
- **IMPReS is a part of both Smart Processes and the MacroProject**

Assumptions & Constraints

- The IMPReS project must meet the requirements of the Product Realization MacroProject and the Smart Processes project.
- DP funding is limited to three years.
- Dual use and external partnerships are strongly encouraged
- The IMPReS project is a driver to enhance teaming within the polymer RD&A community at Sandia

MacroProject Requirements

- small lots of WR quality product
- high fidelity
- knowledge-based design assistants
- maximum use of commercial tools
- integration of project elements

IMPRES Goals

- Develop a polymer methodology within the Sandia "Smart Processes" template to enable engineers to design polymeric structural components from their desks and realize product in weeks.
- To be able to assure part performance and reliability for all parts.

Scope of the Project

- Develop and document the process technology necessary to manufacture resin transfer molding parts at Sandia.
- To obtain or develop the fluid, thermal, and mass transfer codes needed to model and understand the RTM process.
- To develop performance criteria for finished parts fabricated with RTM.
- To be able to transfer this knowledge to qualified vendors to meet DP needs.

Why Resin Transfer Molding?

- There is strong expected benefit to DP
- RTM is expected by many in the field to become the lead composite process
- There is a requirement from program management to focus on one process
- There is a wealth of new and interesting work in the area in both academia and industry
- Sandia presently has RTM equipment
- Acts as a jumping-off point to other processes

Polymer Processing at SNL

- wide breadth of activities
- we are increasing our look at the outside
- sometimes gets “overlooked” or “discounted” in comparison with metals
- excellent reputation

The Need for a Unifying Project

- Polymer RD&A is split over two separate sites
- Work includes personnel from more than four centers
- Need to increase emphasis on processing

Project Deliverables

● FY 95

- Benchmark existing RTM processes and models
- Develop the skillbase to fabricate RTM parts
- Begin assembling necessary modeling capabilities

● End of Project

- Deliver a resin transfer molded part that has been manufactured using the IMPReS-developed model by 9/97
- Prepare a report that defines the technologies developed under IMPReS in manner useful to design engineers
- To have a package that can be transferred to vendors to insure production of WR quality product.

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Modeling and
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APPENDIX B—PROCESS AND PERFORMANCE MODEL OVERVIEW

Charts provided by Steve Burchett.

Sandia National Laboratories

Albuquerque, New Mexico 87185

date: September 9, 1995

to: J. E. Costa, 8711, MS9402

from: S. N. Burchett, 1517, MS0443

subject: IMPReS Computational Modeling Plan

The goal of IMPReS is to develop a computationally based virtual design and manufacturing environment for polymeric structural parts which will allow rapid realization of product. The computational objectives of this program is to: 1) develop a verified computational capability to predict the response of polymeric structural parts which are fabricated using resin transfer molding, 2) develop a verified computational capability to predict operating parameters for processing a reactive polymer system in a resin transfer molding operation, and 3) develop the computational capability in a generalized form such that the capability could readily be applied to other polymeric processes such as encapsulation, injection molding, etc. The purpose of this memo is to define the computational statement of work for IMPReS for the current year.

Figure 1 is a preliminary proposed computational flow model for polymer processing and IMPReS. Using this model I have tried to identify development activities that are required by IMPReS but not currently being addressed. Currently there are substantial ongoing activities which are necessary for IMPReS but are being funded by other programs. This flow model is an attempt to identify the big picture so that there wont be duplication of effort. For instance, the capability to automatically mesh a structure directly from a Pro-Engineer database is a substantial program being funded by several agile manufacturing programs. Based upon this model, I have identified three tasks which need to be addressed and fit within the budget requirements of IMPReS.

TASK#1: Develop a verified capability to predict end product mechanical properties based upon selected resin systems and reinforcement. This task would also include defining the required characterization of the resin and reinforcement. I originally acquired the services of Ann Marie Sastry, 1518, to do this task, however, Ann Marie has accepted a position at the University of Michigan and will not be available. I am actively searching for a replacement. (0.1FTE, \$24K)

TASK #2: Develop a verified failure model for structural polymeric parts. This failure model is to be used to evaluate end product designs before commitment to manufacture. I have acquired the services of Khanh Trinh, 8742, for this activity. (0.2FTE, \$61K)

TASK #3: Evaluate the applicability of available fluid flow computational programs to adequately predict the fluid flow response during filling of a resin transfer mold and to evaluate various processing parameters. This activity also includes making contacts with NIST to determine if joint activities in this area might be desirable. I have acquired the services of Rekha Rao, 1511, to perform this task. (0.2FTE, \$60K)

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MS9402	8742	K. Trinh

FIGURE 1: PRELIMINARY COMPUTATIONAL FLOW CHART

MODELING ASSOCIATED WITH RTM

- **BRIEF INTRODUCTION (Steve Burchett)**
- **SUMMARY OF FLOW EQUATIONS (Rekha Rao)**
- **MECHANICAL MODELING (Ann Marie Sastry)**
- **MECHANICAL MODELING (Khanh Trinh)**
- **FLOW MODELING (Jill Schwegal & Rekha Rao)**

OVERVIEW OF POLYMER PROCESS MODELING AT SANDIA NATIONAL LABS

Sandia
National
Laboratories

Engineering Sciences Center

POLYMER PROCESSING: FLUID

FLUID FLOW

POLYMER PROCESSING: TRANSITION

SOLIDIFICATION: Reacting/Curing

POLYMER PROCESSING: SOLID

IN-SERVICE RESPONSE

FY95 FUNDING FOR MODELING WAS INTENDED TO EVALUATE THE STATE OF TECHNOLOGY WHICH WOULD BE REQUIRED TO PUT IN PLACE UNIFIED DESIGN / MANUFACTURING CAPABILITY FOR RTM

TASK #1: Evaluate the applicability of available fluid flow computational programs to adequately predict the fluid flow response during filling of a resin transfer mold and to evaluate various processing parameters.

TASK #2: Develop a verified capability to predict end product mechanical properties based upon selected resin systems and reinforcement.

- LITERATURE REVIEW
- EVALUATION OF APPLICABILITY OF USING ROM

TASK #3: Develop a verified failure model for structural polymeric parts. This failure model is to be used to evaluate end product designs before commitment to manufacture.

- OMITTED

TOTAL MODELING BUDGET (Approximately 0.5 FTE , 145K)

COMPUTATIONAL ISSUES FOR IMPLEMENTATION OF "INITIAL" AGILE PROCESS FOR RTM

- ① Flow modeling
 - How much detail is required?
- ② EFFICIENT MECHANISM TO PREDICT MATERIAL MECHANICAL PROPERTIES (FINISHED MATERIAL)
- ③ FAILURE PREDICTION
 - INITIAL
 - PROGRESSIVE FAILURE

Flow Models For STM

Why?

APPENDIX C—FLOW MODEL EVALUATION

Charts and text provided by
Jill Schwegel (ProMOLDESIGN and C-Mold)
and by Rekha Rao (FIDAP and GOMA.
Experimental mold filling pictures provided by Tom Bennett.

IMPreS: Overview of Flow Modeling Benchmark Study

Engineering Sciences Center

OVERVIEW OF RTM CODES AVAILABLE AT SNL

- *ProMOLDESIGN*
- *CSET*
- *FIDAP*
- *GOMA*
- equations solved
- numerical methods used
- advanced capability of the codes

ProMOLDESIGN (*ProEngineer*)

Engineering Sciences Center

Simple design tool which gives qualitative results

- **point-and-click interface**
- **calculates front location based on conservation of volume**
- **no reinforcement is modeled**
- **no inflow velocity specified**
- **no detailed flow or pressure field are calculated**

No Advanced features

CSET (CAE Engineering)

Engineering Sciences Center

**More sophisticated simulation package targeted for RTM flow modeling.
Black-box approach: details of how modelling is done are not given.**

“21/2-D” Implementation of Brinkman Equations (neglecting inertia, Newtonian viscosity)

$$\left(\frac{\mu}{K}\right) \bullet u = -\nabla p + \mu \nabla^2 u$$

$$\nabla \bullet (bu) = 0$$

Numerical Method

- finite element in space
- finite control volume to track free-surface location

Advanced Capabilities

- energy equation
- extent of reaction
- in-plane anisotropy (no permeability tensor)

General purpose moving boundary flow code: in development

UNSATURATED FLOW MODEL NOT CURRENTLY WORKING!

2-D (nominally 3-D) Implementation of two-phase Darcy Equations

Numerical Method

- finite element in space, finite difference in time
- moving mesh or capillary pressure used to track free-surface location

Advanced Capabilities

- energy equation
- extent of reaction
- true anisotropy (permeability tensor)
- non-Newtonian viscosity (dependent on extent of reaction, shear-rate, temperature ...)
- multiphase approach - could predict void formation

FIDAP(*Fluid Dynamics International*)

Engineering Sciences Center

General purpose fluid modeling code

Fully 3-D Implementation of Forchheimer-Brinkman Equations

$$\frac{\rho}{\phi} \frac{\partial u}{\partial t} + \left(\frac{\rho \hat{c}}{\sqrt{K}} \|u\|^m + \frac{\mu}{K} \right) \cdot u = -\nabla p + \nabla \cdot \left(\mu \left(\nabla u + \nabla u^T \right) \right)$$
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$

Numerical Method

- finite element in space, finite difference in time
- volume-of-fluid technique used to track free-surface location

Advanced Capabilities

- energy equation
- extent of reaction
- true anisotropy (permeability tensor)
- non-Newtonian viscosity (dependent on extent of reaction, shear-rate, temperature ...)

Generic Preform and Resin Properties

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Preform Properties (*Ahn, et al.*)

volume fraction	K_x (m ²)	K_y (m ²)	K_z (m ²)
0.3	3.2e-9	7.0e-9	7.0e-11
0.4	7.0e-10	9.0e-10	1.1e-11
0.5	1.0e-10	1.5e-10	2.0e-12

Resin Properties

viscosity = 100cp, 200cp

density = 1 g/cm³

injection rate = 37.5 ml/min

2D Flat Panel Mesh for FIDAP

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11/2/95

/home/irrao/documents/impres/impres_vug.fm

Initial Injection Pressure vs. Porosity: 2D FIDAP Results

3D Fidap Mesh for Flat Panel

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11/2/95

/home/irao/documents/impres/impres_vug.fm

3D Results from FIDAP: RTM Processing of Flat Panel ($\phi=.4$, $\mu=200\text{cp}$)

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time = 94 s

3D Results from FIDAP: RTM Processing of Flat Panel ($\phi=.4$, $\mu=200\text{cp}$)

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11/2/95

/home/rrao/documents/impres/impres_vug.fm

FIDAP Difficulties...

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PROBLEMS IMPORTING P3 MESHES

- Steve Burchett was planning to mesh the curved panel mesh with inhouse mesh generation software
- Inhouse mesh would be translated to a PATRAN version P3 mesh
- P3 meshes cannot currently be imported into FIDAP7.5
- PDA and FDI have been contacted (older versions of the codes supported translation)
- We should have a workaround in the near-term

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CONCLUSIONS

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- **Anisotropic Preform Properties**
- **Initial Resin Flow in Flat Panel is Truly 3D**
- **2D and 3D Pressure are in Good Agreement**
- **3D Analysis is Expensive (7 hrs for 1000 time steps on IBM SP2)**
- **Experimental Validation Work Needed to Determine Importance of 3D Effects**

date: November 7, 1995

to: Distribution

from: R. R. Rao, MS 0826, Org. 9111

subject: FIDAP and GOMA flow modeling for resin transfer molding processes

Resin transfer molding (RTM) involves the high pressure injection of a thermosetting resin into a mold filled with a reinforcement. The resin infiltrates the porous reinforcement, making a high-strength, low-density composite part. A heat load is applied to the mold so that the material will cure as it flows. The physical process of interest is the displacement of one fluid (air) by the curing, temperature dependent resin in a porous material. The resin flows into the mold from the injection port, of which there can be more than one, and out through vents in the mold. The vents are placed strategically so that air pockets, which are defects, do not remain in the completed parts. Rough design calculation are often carried out to aid in placement of the vents. These can be done with simplified, easy to use software packages such as ProMOLDESIGN which does not include the porous web or the fluid material properties, but calculates the air pocket locations based on the part geometry.

More complicated process models can be used to calculate the temperature distribution in the mold and the degree of cure of the resin. Process modeling tools are generally more difficult to use, but include more of the process physics than design tools. Process models can give information about the ultimate properties of the part, since temperature and degree of cure will be used to determine the residual stresses in the composite part. This in turn will lead to a prediction of the dimension stability of the part. The application of the heat load to the mold must be done carefully so that the resin can completely fill the mold without over curing and creating voids. This is another area in which detailed process modeling can be useful. Prediction of defects is required to allow optimization of high-quality composite part production. Detailed modeling tools are also needed to predict phenomena such as race-tracking or interlayer flow when layered webs are used.

Requirements for a code suitable for detailed process modeling include anisotropic and variable porous preform permeabilities, multiple dimensions, viscosity as a function of temperature and extent of reaction, multiple inflow and vent location etc. We would also like a code that is general purpose enough to be used for simple design calculations, but that can also be used for more complex process flow calculations. The code will need to calculate velocity, pressure, temperature and extent of reaction throughout the mold.

A benchmark study has been undertaken to compare a commercially available code for resin transfer molding, FIDAP, with an in-house Sandia computer code, GOMA. This benchmark study is

performed in conjunction with Jill Schwegel (8714) who tested CSET, which is another commercially available software package. CSET is designed specifically for RTM applications and uses a two-and-one-half dimension implementation of the Brinkman equation. The Newtonian, inertialess porous flow equations are solved with a finite element method while a finite control volume is used to track the location of the free-surface [1].

Two benchmark problem geometries have been chosen: A flat panel mold and a bowl-shaped curved panel mold. These corresponded to real RTM molds that had been produced for this project. Initially, permeability measurements were to be made on the preform materials used in the mold to give realistic data for the simulation. The modeling results would then be validated with short shot experiments or for the flat panel mold, flow visualization using a glass-fronted RTM mold. For simulating flow through porous media, permeabilities are critical inputs since they contain all the physics of the interaction of the resin with the preform including wetting and pore geometries. In fact, an active area of research involves the theoretical prediction of permeabilities from flow properties and pore geometry models [2, 5].

It is essential that representative permeabilities values be available if there is to be any hope of matching simulations to validation experiments. Unfortunately, lab data for permeabilities was unavailable and the validation studies were not carried out in time to compare to modeling results.

Since laboratory data on the preforms used in our RTM part production were unavailable, permeability values were obtained from the literature. Three different porous web volume fractions, leading to three different sets of permeabilities were to be modeled for each geometry. These are given in Table 1 and are obtained from the experimental data of Ahn et al. [3]. These permeability numbers are for glass fabric mat preforms. The mats are nearly isotropic in the x-y plane, but permeabilities are much lower in the z-direction making the preforms anisotropic.

Table 1. Principal permeability for glass fabric mat preform as a function of fiber volume fraction

volume fraction	$K_x (m^2)$	$K_y (m^2)$	$K_z (m^2)$
0.3	3.2e-9	7.0e-9	7.0e-11
0.4	7.0e-10	9.0e-10	1.1e-11
0.5	1.0e-10	1.5e-10	2.0e-12

The sensitivity of the code to viscosity will be tested by running simulations at two different viscosities: 100 cp and 200 cp. These viscosity values were chosen arbitrarily and do not reflect the actual viscosities of the resins used experimentally. The density of the resin was assumed to be 1 g/ml. The injection flow rate used is from an actual experimental setup and is 37.5 ml/min [4].

The benchmark problems are considerably simplified compared to real resin transfer molding in that temperature and curing effect have been ignored for the preliminary evaluation of the software packages. This scoping effort has assumed that the process is isothermal and that the material

properties are constant throughout the domain, so we are essentially solving only a flow through porous media problem. However, it is critical that any computer program we choose be more general-purpose than needed for the preliminary modeling effort. For future work, it must have the ability to solve more realistic problems that include chemically reacting flow, viscosity as a function of extent of reaction and a detailed representation of the temperature field.

Background and Results from FIDAP

FIDAP is a general purpose finite element code that can be used to solve a variety of fluid dynamics problems. Recently, a mold filling capability has been added to the code based on a volume of fluid algorithm. The mold can either be empty or contain a preform. If the mold is filled with a preform the flow through porous media option is used and permeabilities are defined for the material. Input parameters for FIDAP include mold geometry, fluid density and viscosity, permeabilities for the fiber preform, direction of gravity, vent and injection port location, inflow velocity or injection pressure. The permeability data can vary in complexity from isotropic, to an anisotropic permeability defined only in the principal directions, to a full permeability tensor. Using a full permeability tensor allows the user to solve problems where the problem axes are not aligned with the principal directions of the porous preform and takes into account the cross-flow, which can often be significant [5].

The Forchheimer-Brinkman model is used to represent the porous flow: this is a generalization of the Darcy model for flow in saturated porous medium [6]. The equations solved are the momentum equation,

$$\frac{\rho}{\phi} \frac{\partial u}{\partial t} + \left(\frac{\rho \hat{c}}{\sqrt{K}} \|u\|^m + \frac{\mu}{K} \right) \cdot u = -\nabla p + \nabla \cdot \left(\mu \left(\nabla u + \nabla u^T \right) \right) + \rho g \quad (1)$$

here written in vector form, where u is the volume averaged velocity vector, $\|u\|$ is the magnitude of the velocity, m is the Forchheimer coefficient, p is the pressure, μ is the fluid viscosity, $\bar{\mu}$ is the effective viscosity, ρ is the fluid density, ϕ is the porosity of the porous medium, K is the permeability tensor of the porous media, g is the gravity vector and $\hat{c}$ is the inertia coefficient. If we choose $\hat{c} = 0$ we obtain a Brinkman model of the porous media. The Brinkman model is used for the present work as there is currently no data available for estimating Forchheimer coefficients.

The continuity equation, representing conservation of mass, for an incompressible fluid is

$$\nabla \cdot u = 0 \quad (2)$$

An advection equation is used to track the location of the advancing front.

$$\frac{\partial F}{\partial t} + \nabla \cdot F = 0 \quad (3)$$

Equations 1 and 2 are solved using a finite element method for the spatial discretization and a backward-Euler finite difference method for the integration in time[6]. A volume-of-fluid method is used to locate the free surface at each time step. In addition, special heuristics are used to ensure that

mass is conserved at the free surface [7]. FIDAP also includes equations to model the curing reaction of the epoxy and the energy transport in the system, if that were desired.

Simulations of the filling of the flat panel mold were carried out in both two and three dimensions. This will allow us to determine the importance of three-dimensional effects. Also, since two-dimensional problems are much more efficient to run than the fully three-dimensional calculations we can test the sensitivity of the filling simulations to changes in preform volume fraction, and thus permeability, and viscosity. If the results are relatively insensitive to changes in material properties, we can reduce the number of three-dimensional calculations that need to be done. (Two-dimensional problems are much more efficient to run than three-dimensional ones since computational time scales with the size of the bandwidth squared times the number of unknowns. The bandwidth is much larger for three-dimensional problems, thus a three-dimensional problem will take much longer than a two-dimensional problem with the same number of unknowns.)

The finite element mesh for the two-dimensional flat panel study is shown in Figure 1.

Figure 1: Finite element mesh for two-dimensional RTM simulations

The plate dimensions are 31.6 cm by 31.6 cm and it has a thickness of 0.635 cm. The injection port is 3.8 cm in from the bottom of the plate on the plane of symmetry. In the real mold, the injection port

comes out of plane in the positive z-direction. In the two-dimensional simulation we solve only half the problem since the domain is symmetric; this will significantly reduce the computation time. We simulate the injection port by placing the inflow in the x-y plane on the plane of symmetry. Gravity in the simulation goes in the negative y-direction.

The boundary conditions for the two-dimensional simulations are also shown in Figure 1. We apply a no penetration boundary condition at the mold wall, implying no normal velocity, but the fluid is free to slip tangentially. This is a standard flow through porous media boundary condition and when the Darcy equation is used it is the only velocity boundary condition that can be applied at the wall [8]. This alleviates the need to discretize the thin viscous boundary layer that is present at no-slip boundaries that we are not interested in for the bulk flow calculations. In fact, the behavior near the wall is hard to predict since it depends on how well the preform fits in the mold. One of the most common defects in RTM parts is caused by "race-tracking" where the resin flows unimpeded between the preform and the wall, in a highly permeable region.

We also apply a symmetry condition enforcing no flow across the plane of symmetry. The complexity of reducing three-dimensional reality to a two-dimensional simulation is seen in our application of the inflow boundary condition. We actually place the injection port on the plane of symmetry with inflow in the x-direction. The size of the inflow port was arbitrarily assumed to be 0.635 cm and that based on the inflow rate of 37.5 ml/min, gives a linear inflow velocity of 0.38 cm/s in the positive x-direction. We apply this as a plug flow velocity profile.

Six different transient two-dimensional simulations were carried out at the two viscosities and three different volume fractions. However, for the given constant inflow rate, changing permeabilities and viscosities only has the effect of changing the maximum pressure needed to inject the resin, since the fill time and flow path remain relatively unchanged. Thus, detailed figures will only be given for one volume fraction using one viscosity.

Figure 2 shows the maximum pressure (red line) and the location of the free surface (black line) as a function of time for a two-dimensional RTM simulation for a solid volume fraction of 0.5 and a viscosity of 200 cp. The contours shown go from the maximum value at the inlet and drop off in even intervals to a pressure of zero at the free surface. The flow spreads out from the injection port in an ellipsoidal fashion, reflecting the difference in the x and y permeabilities. Gravity effects do not seem important since the flow is basically symmetric in the y-direction. The injection pressure increases over time to maintain the constant inflow rate. This is because over time the flow path becomes larger necessitating a larger pressure drop in order to maintain the same pressure gradient. We can see that we get a sharp direction change in the isobaric surface when the material hits the corner of the mold and starts interacting with the vertical wall. From the shape of this surface, we can see that bottom corners are possible locations of trapped air, which can then lead to defects in the composite part.

Figure 2: Maximum pressure and free surface location as a function of time for two-dimensional RTM simulations (solid volume fraction =0.5, $\mu=200\text{cp}$)

A summary of the results for all six calculations are given in Figure 3, which shows the initial injection pressure as a function of the solid volume fraction. The initial injection pressure is essentially linear on a semilog plot with preform volume fraction, implying that pressure increases exponentially with solid volume fraction.

Figure 3: Initial maximum injection pressure as a function of preform volume fraction for two-dimensional RTM simulations

From Figure 3 we can see that there is almost no effect on the initial injection pressure when the viscosity is doubled: the curves for viscosity of 100cp and 200cp essentially lie on top of one another. However, as we go to higher volume fraction we see large changes in the pressure field. If we increase the preform porosity from 0.3 to 0.5 the pressure increases by 10^5 . From this, we can conclude that porous flow effects dominate the flow masking any viscous or gravitational effects. Also, once experimental data is available, it will be interesting to compare the pressure from the simulation with the laboratory pressure to determine whether the sensitivity to solid content is a physical effect or a numerical artifact.

Since there was little change in the flow field and free surface locations with changes in volume fraction and viscosity, only one three-dimensional simulation was carried out. The three-dimensional mesh is shown in Figure 4. As before, we need only solve half the problem since the geometry is symmetric and the boundary conditions are no penetration at the solid surface and no flow across the

symmetry plane. For the fully three-dimensional problem, we can have a more realistic injection port that comes in from the positive z -direction. Since we had no information about the geometry of the injection port, only the volumetric inflow rate was known, an easy to mesh injection port was created in a rectangular geometry. The injection port is 0.635cm by 0.635cm wide and 8cm long to insure that the flow is fully developed where it is applied. A plug flow velocity of 0.38cm/s is input at the mouth of the injection port in the negative z -direction.

Figure 4: Finite element mesh for three-dimensional flat panel RTM simulations

After carrying out the six two-dimensional simulations, it became clear that inertial and viscous effects were relatively unimportant compared with the porous flow effects. For this reason, the three-dimensional simulations were simplified by ignoring inertial effects. If we ignore inertial effects, the momentum equation, equation 1, loses its transient term and becomes pseudo-steady and the only remaining transient equation is the filling equation, equation 3. Thus, the time-step size is determined only by the filling equation, which is much larger than the time-step which would have been determined by the momentum equation. Using a larger step size allows us integrate to the final fill time more quickly. In fact, the difference in time-step size was so large, that if this simplifying assumption had not been made, no solution would have been achieved. (The solution presented below was expensive to calculate. It took 12 cpu hour on a IBM SP2 to solve at a cost of \$20/cpu hour.)

The momentum equation is a vector equation, meaning it has one to three components depending on the dimensionality of the problem. In two-dimensions, the two components of the momentum equation coupled with the continuity equation, and the filling equation are solved simultaneously using the direct solver in FIDAP. In three-dimensions, it is not possible to use the direct solver since

the matrix is too large to be solved in a reasonable amount of time. For this reason, the segregated solver is used for three dimensional problems. The segregated solver solves each equation, three momentum equations, the continuity equation and the filling equation, separately and then iterates until convergence [9]. Since the equation set is linear, convergence generally occurred fairly quickly.

The three-dimensional filling profile at a fill time of 94s is given in Figure 5.

Figure 5: Filling profile at a fill time of 94s for three-dimensional RTM simulation

From Figure 5, we can see that the flow proceed from the injection nozzle into the porous preform with the movement of the fluid hampered by the low permeability of the preform in the z-direction. (The z-permeability is about two orders of magnitude smaller than the in-plane permeabilities.). This is evident from the filling profile that clearly demonstrates that more fluid has reached the back of the plate abutting the injection port than has reached the front of the plate. So it is clear, that at least initially, the flow is truly three-dimensional. This lag in the velocity profile from the back to the front of the mold could never have been predicted using a two-dimensional or a two-and-a-half dimensional model such as CSET.

Over time, we can expect the front-plate profile to catch up with the back-plate profile and the flow to take on a two-dimensional character. This is because the fluid will flow in the z-direction in response to the z-pressure gradient caused by the disparity in filling. We can see the evolution of the flow from three-dimensional to two-dimensional in Figure 6, which gives the flow profile at 591s.

Figure 6: Filling profile at a fill time of 591s for three-dimensional RTM simulation

In Figure 6, we can clearly see that the filling profiles are identical on the front and back plates and that the flow field now progresses in a two dimensional manner. It is important to note that the two-dimensional and three-dimensional initial injection pressures are in good agreement: 0.42×10^8 Pa versus 0.33×10^8 Pa.

The three-dimensional flat panel mesh was produced using the meshing tools available in FIDAP. The curved panel mold had a much more complicated geometry, so that it was decided that Steve Burchett would make the mesh using the EXODUS preference of PATRAN. This allowed him to take the ProEngineer geometry and mesh it directly. Unfortunately, FIDAP 7.5 and PATRAN P3 are no longer compatible and we can no longer import a P3 mesh into FIDAP without losing important information that leaves us unable to put boundary conditions on the mesh, making it impossible to run a simulation. FDI, the makers of FIDAP, and PDA, the makers of PATRAN, have both been contacted extensively and offered work-arounds that did not alleviate the problem. Both FDI and PDA are working on the problem and should have it fixed at some point, since it is an advertised capability of FIDAP to read in PATRAN meshes. Unfortunately, since the curved panel mesh could not be read into FIDAP, no benchmark results are available for this geometry.

Background and Results from GOMA

GOMA is a multiphysics Sandia code designed to simulate a variety of manufacturing applications. It can solve incompressible fluid flow, nonlinear deformation of solids, multispecies transport equations, temperature fields as well as flow through porous media using the finite element method for the spatial discretization and the finite difference for temporal discretization. The type of applications that GOMA development has focused on have been free and moving boundary problems

that have a free surface, the location of which is unknown *a priori* to the simulation and must be solved as one of the unknowns.

The porous flow equations available in GOMA are two-phase implementation of Darcy's equation for flow in unsaturated porous media, the details of which can be found elsewhere [9,10]. The important thing to note is that with the two-phase porous flow equations, it will be easier to predict the location of trapped air pockets that can lead to defects in the final part.

Unfortunately, when this work was carried out in September of 1995, there was a bug in the transient implementation of the two-phase Darcy's equation. Thus, while this benchmark study was being conducted no two-phase solutions could be obtained. The error in the code has since been corrected and some preliminary results were obtained. However, no in depth work was carried out and so no results from GOMA will be presented here.

Conclusions

Two and three-dimensional simulations of RTM processing have been carried out with the commercial finite element software package FIDAP. The results of this work demonstrate that FIDAP has all the physics required to successfully model the manufacturing of RTM parts including flow through porous media, curing reaction and heat transport. FIDAP performed well on the benchmark problems and can be used in either two or three-dimensions depending on the degree of detail needed from the modeling results. It is my recommendation that if any future RTM modeling work is to be done using commercial software, FIDAP be used. Also, at that time GOMA should be reevaluated if more customizable in-house software is desired.

References

1. T.-Y. Chen and V. W. Wang, "A Unified Simulation for Reactive Polymer Processing: RIM, SRIM and RTM," p. 2421, ANTEC '93.
2. R. B. Saeger, L. E. Scriven and H. T. Davis, "Transport Processes in Periodic Porous Media," Journal of Fluid Mechanics, p.1, volume 299 (1995).
3. S. H. Ahn, W. I. Lee and G. S. Springer, "Measurement of the Three Dimensional Permeability of Fiber Preforms using embedded Fiber Optic Sensors," Stanford University Report to Sandia National Laboratories, October, 1993.
4. J. Schwegel, personal communication.
5. M. V. Bruschke, *A Predictive Model for Permeability and Non-Isothermal Flow of Viscous and Shear-Thinning Fluids in Anisotropic Fibrous Media*, Ph.D. Thesis, University of Delaware, August, 1992.
6. Fluid Dynamics International, FIDAP User's Manual, FIDAP 7.0, 1993
7. Fluid Dynamics International, FIDAP Update Manual, FIDAP 7.5, 1995.

8. J. Bear, *Dynamics of Fluids in Porous Media*, Elsevier, NY (1972).

9. P. R. Schunk, P. A. Sackinger, R. R. Rao, K. S. Chen and R. A. Cairncross, "GOMA - A Full-Newton Finite Element Program for Free and Moving Boundary Problems with Coupled Fluid/Solid Momentum, Energy, Mass, and Chemical Species Transport: User's Guide," SAND95-????, to be published.

10. M. J. Martinez, "Formulation and Numerical Analysis of Non-Isothermal Multiphase Flow through Porous Media," SAND94-0379.

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The Evolution to C-MOLD

Rapid Tooling
LDRD

Pro/ENGINEER

Pro/MOLDESIGN

C-MOLD
Reactive Molding

Pro/MOLDESIGN

- ❖ C-Flow/EZ® performs mold flow analysis based on an assumption of a Newtonian fluid and internal condition.
- ❖ Input is via a compressed shell mesh (2-D) with inlet ports indicated by datum point(s). Hypothetical hot or cold runners can be added to the model along with a “shape factor” to define the geometry.
- ❖ Output from the flow analysis is in a graphical format that displays possible air traps, weld lines, melt front, velocity based on percent of fill, and recommended ram speed.

C-MOLD Reactive Molding

- ❖ C-Mold Reactive Molding analysis is based on a “hybrid finite-element/finite-difference method to solve pressure and temperature fields and a control volume method to track moving melt fronts.”
- ❖ Mold filling is modeled using a “generalized Hele-Shaw flow” for areas without reinforcement and with Darcy’s Law for areas with reinforcement.
- ❖ Analysis assumes an “incompressible viscous polymeric resin filling the cavity under non-isothermal conditions and symmetric thermal boundary conditions.”

C-MOLD Reactive Molding User’s Guide, pg 1-2

C-MOLD Reactive Molding

- ❖ C-Mold Reactive Molding “can handle a three-dimensional thin cavity with a melt-delivery system that may contain hot or cold, circular or non-circular runners.”
- ❖ “The program simulates the dynamics of fluid flow, heat transfer and curing of resins during filling, and heat transfer and curing during post-filling.”

C-MOLD Reactive Molding User's Guide, pg 1-2

C-MOLD Reactive Molding - Input

In order to run an analysis, the following material data sets must be entered:

Resin:

- ❖ Constant polymer density
- ❖ Constant polymer specific heat
- ❖ Constant polymer thermal conductivity
- ❖ Reactive polymer viscosity I
- ❖ Constant gelation conversion
- ❖ N-th order kinetics w/induction time

Fiber:

- ❖ Constant fiber density
- ❖ Constant fiber specific heat
- ❖ Constant fiber thermal conductivity
- ❖ Fiber-mat porosity and permeability

C-MOLD Reactive Molding - Input

In addition to the material properties, the following processing conditions must be entered:

- ❖ Fill time
- ❖ Inlet melt temperature
- ❖ Mold temperature
- ❖ Fill-to-pack switch-over by percent volume
- ❖ Pack-to-open switch-over by ejection conversion
- ❖ Inlet melt initial conversion

Models Used - Flat Panel

PANEL 12.45 X 12.45 X .25 THK

Models Used - Curved Box

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SECTION A-A

Output Examples - Air Gaps

Output Examples - Air Gaps

By adjusting the location of the inlet port, the designer is able to move the vent away from the curved surfaces and place it in a location that is easier (less expensive) to machine.

Output Examples - Melt Front

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“Spectre colors represent relative advancement of the front. The blue areas are the earliest to be filled; the red ones - the latest.”

Pro/MOLDESIGN User's Guide, pg. 3-7

Output Examples - Melt Front

Output Examples - Velocity

25% Filled

75% Filled

Real Life Examples

16

Curved Box #3

- ❖satin weave fabric
- ❖approx. 35% volume fraction

Real Life Examples

92

Curved Box #2

- ❖satin weave fabric
- ❖approx. 35% volume fraction

Output Examples - Velocity

25% Filled

75% Filled

“The length of the vector shows relative magnitude, the direction minus the direction of the flow.”

Pro/MOLDESIGN User's Guide, pg. 3-7

Real Life Examples

94

Curved Box #4

- ❖satin weave fabric
- ❖low volume fraction

Real Life Examples

Curved Box #5
❖ continuous strand mat
❖ low volume fraction

RTM MOLD FILLING IN FLAT PANEL

30% glass mat fiber volume with Epon 862/Epicure W resin

30 seconds

250 seconds

500 seconds

1000 seconds

1500 seconds

1700 seconds

APPENDIX D—COMPOSITE MODEL EVALUATION - MECHANICAL PERFORMANCE

Charts and text provided by Ann Marie Sastry.

ANALYSIS OF COMPOSITE STRUCTURES MADE BY RESIN TRANSFER MOLD PROCESSING

Report to:
Sandia National Laboratories
IMPreS Program
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EXECUTIVE SUMMARY

Composite materials produced by liquid molding processes offer the advantages of high structural performance and low weight, with manufacturability at low cost.

Replacement of traditional laminated composites with liquid molded composites offers potential savings, both in prototyping and production, with a greater range of possible component geometries. Resin Transfer Mold (RTM) processing, one type of liquid molding, has been identified as a versatile, economical method for production of composites. Typically, the reinforcement phase in these materials is a fabric, either nonwoven or woven. A preform comprised of the dry textile phase is placed in a closed mold, which is filled with resin (typically a thermosetting resin) and the composite is consolidated at high temperature to cure the resin.

Structural analysis and design of these textile (fabric) composites requires combined analysis of constituents, microstructural arrangement and processing conditions.

Traditional laminate theory, along with exclusive use of simplified rule-of-mixtures approaches to estimate in-plane properties is insufficient for two main reasons: 1) the coupling present in weave geometries significantly affects the elastic response of the materials (rule-of-mixtures approaches neglect this coupling), and 2) parts produced by liquid molding processes are generally of complex geometry, and placement of flat textiles in curved molds produces differences in microstructure, and thus stiffness, in different regions of a particular, complex mold.

Full structural analysis of curved parts thus requires at least three main components: 1) modeling elastic properties of (dry) fabric microstructures, to the fiber or tow level; 2) modeling preform structural response based on the fabric microstructures; and 3) modeling composite properties based on processing information and resin composition. Each of these subjects has been widely researched.

The first area, determination of elastic properties of dry textiles, is well-understood for a variety of commonly available materials. The second area, modeling preform response based on fabric modeling, has been addressed both from the standpoint of strict geometric modeling in preform placement in a mold, as well as the effect of preform displacement during processing, and the resulting effects on composite structural response. The third area, process modeling, has been investigated both empirically and

numerically by a number of workers. There are several key numerical issues associated with rapidly evolving flow fronts, which comprise another area of research in many polymer processes.

Structural analysis of composites of complex geometries for the IMPReS program will incorporate these different aspects of modeling. Both commercial and SNL codes will be used to carry out structural analyses, with close attention paid to microstructure on an element-by-element basis. Teaming with the fluid modelers in cooperation with performance of experimental verification of flows through different candidate microstructures will allow development of more accurate structural analysis software. An immediate goal is the benchmarking of commercial and SNL structural analysis codes, given the unique requirements in modeling composites comprised of fabric preforms.

CONSTITUENT MODELING: FROM FIBERS TO FABRICS

Structural modeling of composite components must begin with constituent-level modeling. In this discussion, we use "composites" to mean materials comprised of fibers and polymeric binder, or matrix. Fibers are of small diameter, and are agglomerated into tows, which are larger bundles of aligned fibers (typically 1000-5000 fibers comprise a tow). A lamina refers to a sheet comprised of aligned fiber tows held together by the matrix. In traditional, laminated composites, layers of unidirectional fiber-reinforced laminae are bonded together, with successive layers at angles to one another. In this case, calculation of in-plane stiffnesses can be quite accurately estimated using a series or parallel rule-of-mixtures (ROM) approach, amounting to a volumetric averaging of constituent properties. In the case of estimating properties of fabric structures, however, the interactions of the fiber tows plays an important role in the resulting structural properties.

Classic lamination theory is a continuum approach for estimation of in-plane stiffnesses in a composite laminate plate. Strains are assumed to be small, and the in-plane stiffnesses of individual layers, or plies, are typically calculated using an ROM approach. Because the fibers in each layer are aligned, the assumption that there is no tow coupling is valid, and modeling at the tow level is unnecessary.

In composites comprised of woven fiber reinforcement, however, there is significant tow coupling, i.e. the deformation of the fibrous structure is the result of interaction of individual tows. Furthermore, the use of liquid molding techniques allow manufacture of complex geometries, making the modeling of the microstructure even more important, as the microstructure can be substantially different in a single mold as it is forced to conform to deep draws and corners. Figure 1 shows schematically the forming of a fiber preform from a flat sheet of woven fabric, and subsequent composite production.

Figure 1. High-speed resin transfer molding operation. [from Johnson, 1993]

Modeling of the deformation of fabrics has been the subject of much study, beginning by workers in the textiles area in the first part of this century. One of the earliest models to incorporate fiber geometry into fabric deformation mechanics was that put forward by Peirce [Peirce, 1937]. Peirce used a simplified geometric model of contacting fibers to model the deformation in a fabric. This classic geometry has been used extensively, and in recent solid modeling efforts of analysis of yarns and woven assemblies which use limiting contact geometries to analysis fabrics at the level of a single fiber [Keefe, 1992, 1994a, 1994b].

Use of simplified geometric models for fabrics has produced three main types of analytic models for fabric microstructures. A series of analyses by Ishikawa and co-workers [Ishikawa and Chou, 1982a,b] produced three basic microstructural models for different types of fabric microstructures: the mosaic model, the crimp model and the bridging model. Because infinitesimally small elements within each model microstructure is assumed to follow laminate theory, these models are classified as laminate theory models.

Figure 2. Schematic representation of assumed geometry in the mosaic model. [from Byun and Chou, 1989]

Figure 3. Schematic representation of assumed geometry in the crimp (undulation) model. [from Byun, 1989]

Figure 4. Schematic representation of assumed geometry in the bridging model [from Byun, 1989].

Two dimensional woven composites have been analyzed using other applications of micromechanics [Naik *et al.*, 1992a-e; Shembekar and Naik, 1992; Realff *et al.*, 1993], and the deformation of these structures is understood for standard weaves [Hearle, 1994]. More detailed 3D finite element analyses of 2D structures have also been performed for the simpler 2D weaves [e.g. Ichihashi *et al.*, 1994].

There is also a substantial body of effort in modeling 3D interlocking fabrics. Use of these materials can eliminate the production step of layering 2D fabrics in the mold. 3D fabrics have the advantage over 2D materials in possessing a higher interlaminar strength [Fujita *et al.*, 1993] because of the third dimension of fiber reinforcement. Weaving and braiding advances have increased the available options in 3D woven microstructures, and these processes themselves are the subject of study. Analyses have been performed for varying geometries [Byun and Chou, 1990, 1991; Whitney and Chou, 1989], and computer-aided design methodologies have been developed for weave design of 3D fabrics [Byun *et al.*, 1991; Dastoor *et al.*, 1992; 1994a,b; Du, 1991; Hill *et al.*, 1995a,b; Li *et al.*, 1991].

These analyses represent the first step in modeling preform fabrics. In real use of these materials in liquid molding of composites, draping and forming of the curved structures produced from these fabrics must be additionally modeled.

DESIGN AND MODELING OF FABRIC PREFORMS FOR LIQUID MOLDING

Preforms produced for RTM can be produced by 1) stamping flat fabrics to net shape [Suemasu *et al.*, 1994], 2) filament winding of fibers to net shape [Chou, 1989], or 3) laying successive fabric laminae directly in the mold, covering joint and curves as necessary [Steenkamer *et al.*, 1995]. Formability of these materials into the complex geometries required is of major concern [Cai *et al.*, 1994; Yu *et al.*, 1994].

There are limitations on the ability of a woven to conform to an arbitrary surface, and the competing design goals of high drapability with high flexural rigidity has been studied by several workers. Classic work by Robertson and coworkers [Robertson *et al.*, 1981; 1984] on the draping of fabrics over hemispherical and cone-shaped solids, led to generalized models [e.g. Van West *et al.*, 1990; Aono *et al.*, 1994] for fabric placement on curved surfaces. Figures 5 and 6 demonstrate the problems of interest.

Fig. 4 Diagram showing the angles γ (boundary and diagonal), γ_x and γ_y .

Fig. 5 Photograph of a rounded cone covered with cheesecloth. The cone angle is 69°.

Figure 5. Draping fabric over a rounded cone: analysis and demonstration with cheesecloth fabric [Robertson *et al.*, 1984].

Figure 6. Generalized methodology for prediction of fabric laydown on an arbitrary surface [Van West *et al.*, 1990].

The placement of the preform in the mold, and the resulting deformations of microstructure, have important implications for continuum modeling. Instead of use of a homogeneous model, the different stiffness properties of highly deformed fabric regions in the mold must be taken into account. Figure 7 demonstrates the variability possible in stiffness in a real part of moderately complex geometry.

The mold filling process itself also perturbs fabric microstructure, sometimes necessitating that additional fabric microstructural modelling be performed. This analysis can be combined into a mold filling simulation.

Predicted variation in tensile modulus for undershield swage corner.

Figure 7. Tensile modulus variation predicted in a corner of a complex component [Middleton *et al.*, 1995].

MOLD FILLING SIMULATION AND PROCESS MODELING

Deformation of preforms within the mold during processing can dramatically affect the thermoelastic stresses in a complex composite due to rearrangement of fibers from the flow [Berdichevsky and Cai, 1993; Laroche and Vu-Khanh, 1994; Lundstrom and Gebart, 1995]. Also, matrix rich regions can develop near polymer inlets [Han *et al.*, 1993], affecting structural properties.

Studies on the mechanics of wetting and permeation of fiber preforms have been performed by a number of workers. Transport through porous media has in fact been the subject of scientific inquiry for more than one hundred years [Maxwell, 1881; Meredith and Tobias, 1962]. For fibrous materials, wetting of tows has been studied [Bayramli and Powell, 1992; Chan and Morgan, 1993; Ghali *et al.*, 1994] as a first step in modeling the resin transport. The effects of coatings, or "sizings" on fibers dramatically affects these processes [Larson and Drzal, 1994]. Limited studies on the effects of heat

and mass transfer during "wicking" of fabrics have been carried out [e.g. Ghali *et al.*, 1995] to address the issue of micromechanisms of transport as well.

These microstructural effects are generally neglected in continuum process modeling of RTM, in favor of simplified approaches employing tensor permeabilities to describe flow through the preforms. Process optimization has been done for a variety of materials [e.g. Foley and Gutowski, 1991; Karbhari, 1993; Kendall *et al.*, 1992] and process monitoring has been developed using smart sensors in the mold [e.g. Kikuchi *et al.*, 1995; Kranbuehl *et al.*, 1991; Melotik *et al.*, 1993; Walsh and Charmchi, 1993] to provide data for these continuum analyses. There are a number of workers developing mold-filling simulations for Newtonian flow through fiber beds [e.g. Bruschke and Advani, 1991; Cai, 1992; Carpenter *et al.*, 1993; Chan and Hwang, 1991; Chan and Morgan, 1992; Skartsis *et al.*, 1991a,b; 1994; Um and Lee, 1991; Young, 1994].

Corresponding analyses and experimental projects have been carried out to identify permeabilities for a number of candidate materials [e.g. Adams and Rebenfeld, 1991a,b; Dave, 1990; Verheus and Peeters, 1993]. Advances in the past several years in improved numerical techniques for modeling advancing flow fronts [e.g. Anturkur, 1995; Chang and Kikuchi, 1994; Trochu *et al.*, 1993; and Um and Lee, 1990].

Ultimately, one would like to couple the fluid and structural analyses in order to allow design of tailored microstructures for different applications. There is simultaneously a need for microstructures which are highly permeable to resin, to allow production of well-impregnated, void-free parts and a need to use preforms which are densely-woven, to produce high fiber volume fraction composites with desirable structural properties.

PROPERTIES OF FABRIC COMPOSITE STRUCTURES

Final prediction of properties of textile composites has been attempted for a wide range of failure modes in addition to the work in modeling the elastic properties. Clearly, there is a tight coupling in liquid molded materials between processing, microstructure and net structural response. Thermoelastic effects, important in most composites due to thermal mismatch of fibers and matrix, are particularly important in wovens, since additional thermal residual stress can be present due to twisted yarns [Yao and Chou, 1991]. The fabric geometry has been found to have a significant influence on the thermal

expansion coefficients as well, by both micromechanics approaches [Ganesh and Naik, 1994] and homogenization techniques [Dasgupta and Agarwal, 1992]. These thermoelastic effects must be accounted for in any structural analysis, as thermal residual strains are generally significant when compared to strains in service.

Another important processing-specific issue requiring structural analysis is the effect of applied loads at the boundary of a textile composite component. The edge effects have been shown to be quite significant under shear through finite element analysis [Whitcomb *et al.*, 1995].

Fracture and toughness properties of woven composites are critical; textile composites are often chosen in structural applications due to their higher fracture toughness than their laminated counterparts. Unlike Mode I crack propagations in laminates, fiber tows must fail in tension in 3D materials in order to propagate a crack in a double cantilever beam (DCB) experiment. Interpretation of the load-displacement curves for these materials [Guenon *et al.*, 1989] has shown that these materials exhibit a ten-fold increase in interlaminar toughness over similar 2D wovens. In 2D weaves, the in-plane weave geometry itself has been shown to have a significant effect on interlaminar toughness [Wang and Zhao, 1995].

Failure analysis of joined components has been performed in comparing the differences between types of joints [e.g. Lin and Tsai, 1995]. Structural analysis of these materials will require that satisfactory prediction be made of bolted joint strength. This has been the subject of a great deal of interest in laminated composites over the last twenty years, but the modeling in that class of materials is generally not applicable to wovens.

Various design methodologies have been devised for structural RTM modeling [e.g. Cohen *et al.*, 1994; Molina *et al.*, 1994] which incorporate combinations of flow modeling and simplified solid modeling. There is still a great deal of reliance however, on empirical parameter optimization for new textiles and resins.

CONCLUSIONS AND RECOMMENDATIONS FOR STRUCTURAL ANALYSIS

Advances in analysis of textile preforms have contributed to their wider use in RTM processes. Flow modeling has likewise been advanced through implementation of new micromechanics models and through new numerical approaches.

Both components are necessary in structural modeling of textile composites of complex geometry. While modeling of most of the in-plane properties of flat textile composites is well-understood for a variety of weaves, estimation of structural properties in curved parts is greatly complicated by the shifting of microstructures as they conform to curved surfaces. Gradients in composite properties due to the unique flow patterns arising in complex molds are also of concern in prediction of performance of real materials.

A first approach in continuum structural modeling of complex geometry is to assume that the element-wise properties are identical to those in a flat sheet of the same composition. Work is being performed to compare commercial and SNL finite element codes; future work will involve incorporation of greater detail at the microstructural level. Teaming with the fluid modelers (1511) in cooperation with performance of experimental verification of flows through different candidate microstructures will allow development of more accurate structural analysis software.

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REFERENCES

- Adams, K.L. and L. Rebenfeld, "Permeability Characteristics of Multilayer Fiber Reinforcements. Part I: Experimental Observations," *Polymer Composites* 12(1991) 178-185.
- Adams, K.L. and L. Rebenfeld, "Permeability Characteristics of Multilayer Fiber Reinforcements. Part I: Theoretical Model," *Polymer Composites* 12(1991) 186-190.
- Anturkar, N.R., "Petrov-Galerkin Finite Element Analysis for Advancing Flow Front in Reaction Injection Molding," *Computers & Fluids* 24(1995) 55-62.
- Aono, M., D.E. Breen and M.J. Wozny, "Fitting a Woven Cloth Model to a Curved Surface: Mapping Algorithms," *Computer Aided Design* 26(1994) 278-292.
- Bayramli, E., and R.L. Powell, "Impregnation Dynamics of Carbon Fiber Tows," *Journal of Composite Materials* 26(1992) 1427-43.
- Berdichevsky, A.L. and Z. Cai, "Preform Permeability Predictions by Self-Consistent Method and Finite Element Simulation," *Polymer Composites* 14(1993) 132-143.
- Bruschke, M.V. and S.G. Advani, "RTM: Filling Simulation of Complex Three Dimensional Shell-Like Structures," *SAMPE Quarterly* Oct (1991) 2-11.
- Brushchke, M.V., S.G. Advani and T.L. Luce, "Effective In-Plane Permeability of Multilayered RTM Preforms," *Proceedings of the American Society for Composites Seventh Technical Conference: Composite Materials, Mechanics and Processing* Oct (1992) 103-112.
- Byun, J.H. and T.W. Chou, "Elastic Properties of Three-Dimensional Angle-Interlock Fabric Preforms," *Journal of the Textile Institute* 81(1990) 538-548.
- Byun, J.H. and T.W. Chou, "Modelling and Characterisation of Textile Structural Composites: A Review," *Journal of Strain Analysis* 24(1989) 253-262.
- Byun, J.H., G.W. Du and T.W. Chou, "Analysis and Modeling of Three Dimensional Textile Structural Composites," *High-Tech Fibrous Materials: American Chemical Society* (1991) 22-33.
- Byun, J.H., T.J. Whitney, G.W. Du and T.W. Chou, "Analytical Characterization of Two-Step Braided Composites," *Journal of Composite Materials* 25(1991) 1599-1618.
- Cai, Z., "Simplified Mold Filling Simulation in Resin Transfer Molding," *Journal of Composite Materials* 26(1992) 2606-2629.
- Cai, Z., J.Z. Yu and F.K. Ko, "Formability of Textile Preforms for Composite Applications; Part 2: Evaluation Experiments and Modelling," *Composites Manufacturing* 5(1994) 123-132.

Carpenter, G., R. Leek, T. Donnellan and A. Rubel, "A Simulation of Resin Transfer Molding for a Cubic Shell Geometry," *Heat and Mass Transfer in Materials Processing and Manufacturing* 261(1993) 133-145.

Chan, A.W. and S.T. Hwang, "Modeling of the Impregnation Process During Resin Transfer Molding," *Polymer Engineering and Science* 31(1991) 1149-1156.

Chan, A.W. and R.J. Morgan, "Modeling Preform Impregnation and Void Formation in Resin Transfer Molding of Unidirectional Composites," *SAMPE Quarterly* Apr(1992) 48-53.

Chan, A.W. and R.J. Morgan, "Modeling Preform Impregnation and Void Formation in Resin Transfer Molding of Unidirectional Composites," *SAMPE Quarterly* Oct (1992) 45-49.

Chan, A.W. and R.J. Morgan, "Tow Impregnation During Resin Transfer Molding of Bi-Directional Nonwoven Fabrics," *Polymer Composites* 14 (1993) 335-340.

Chang, L.W., S.S. Yau and T.W. Chou, "Notched Strength of Woven Fabric Composites With Moulded-in Holes," *Composites* 18(1987) 233-241.

Chang, W. and N. Kikuchi, "An Adaptive Remeshing Method in the Simulation of Resin Transfer Molding (RTM) Process," *Computer Methods in Applied Mechanics and Engineering* 112(1994) 41-68.

Chou, T.W. and F.K. Ko, eds., *Textile Structural Composites*, Elsevier: New York, 1989.

Chou, T.W. and K. Takahashi, "Non-linear elastic behavior of flexible fiber composites," *Composites* 18(1987) 25-34.

Chou, T.W. and J.M. Yang, "Structure-Performance Maps of Polymeric, Metal and Ceramic Matrix Composites," *Metallurgical Transactions A* 17A(1986) 1547-59.

Cohen, S.E., C.T. Graves, E. Bernardon and H. West, "Design of a New Composite Forming Process Using a Formal Design Methodology," *International Journal of Materials and Product Technology* 9(1994) 23-41.

Dasgupta, A. and R.K. Agarwal, "Orthotropic Thermal Conductivity of Plain-Weave Fabric Composites Using A Homogenization Technique," *Journal of Composite Materials* 26(1992) 2737-58.

Dastoor, P.H., S.P. Hersh, S.K. Batra and W.J. Rasdorf, "Computer Assisted Structural Design of Industrial Woven Fabrics Part I: Need, Scope, Background and System Architecture," *Journal of Textile Institute* 85(1994) 89-109.

Dastoor, P.H., S.P. Hersh, S.K. Batra and W.J. Rasdorf, "Computer Assisted Structural Design of Industrial Woven Fabrics Part II: System Operation, Heuristic Design," *Journal of Textile Institute* 85(1994) 110-134.

Dastoor, P.H., T.K. Ghosh, S.K. Batra and S.P. Hersh, "Computer Assisted Structural Design of Industrial Woven Fabrics Part III: Modelling of Fabric Uniaxial/Biaxial Load-Deformation," *Journal of Textile Institute* 35(1994) 135-157.

Dave, R., "A Unified Approach to Modeling Resin Flow During Composite Processing," *Journal of Composite Materials* 24(1990) 22-40.

Du, G.W. and T.W. Chou, "Analysis of Three-Dimensional Textile Preforms for Multidirectional Reinforcement of Composites," *Journal of Materials Science* 26(1991) 3438-48.

Foley, M.F. and T. Gutowski, "The Effect of Process Variables on Permeability in the Flexible Resin Transfer Molding Process," *23rd International SAMPE Technical Conference* Oct(1991) 326-340.

Frye, B., "Resin Transfer Molding: The Infrastructure Barrier/Opportunity," *26th International SAMPE Technical Conference* Oct(1994) 417-422.

Fujita, A., H. Hamada, and Z. Maekawa, "Tensile Properties of Carbon Fiber Triaxial Woven Composites," *Journal of Composite Materials* 27(1993) 1428-1442.

Ganesh, V.K. and N.K. Naik, "Failure Behaviour of Plain Weave Fabric Laminates Under In-Plane Shear Loading: Effect of Fabric Geometry," *Composite Structures* 30(1995) 179-192.

Ganesh, V.K. and N.K. Naik, "Thermal Expansion Coefficients of Plain-Weave Fabric Laminates," *Composites Science and Technology* 51(1994) 387-408.

Ghali, K., B. Jones and J. Tracy, "Modeling Moisture Transfer in Fabrics," *Experimental Thermal and Fluid Science* 9(1994) 330-336.

Ghali, K., B. Jones and J. Tracy, "Modeling Heat and Mass Transfer in Fabrics," *International Journal of Heat and Mass Transfer* 38 (1995) 13-21.

Guenon, V.A., T.W. Chou and J.W. Gillespie, "Toughness Properties of a Three-Dimensional Carbon-Epoxy Composite," *Journal of Materials Science* 24(1989) 4168-75.

Hahn, H.T. and R. Pandey, "A Micromechanics Model for Thermoelastic Properties of Plain Weave Fabric Composites," *Journal of Engineering Materials and Technology* 116(1994) 517-523.

Han, K., L. Trevino, J. Lee, and M. Liou, "Fiber Mat Deformation in Liquid Composite Molding. I: Experimental Analysis," *Polymer Composites*, 1994 14(1993) 144-160.

Hearle, J.W.S., "Fabric Mechanics as a Design Tool," *Textile Horizons* 14(1994) 12-16.

Hill, B.J., R. McIlhagger and C.M. Harper, "Weaving of Three-Dimensional Fabrics for Preform Construction Part II: Use of Flat Continuous Glass Filament Yarn," *Journal of Textile Institute* 36(1995) 104-109.

Hill, B.J., R. McIlhagger and C.M. Harper, "Weaving of Three-dimensional Fabrics for Preform Construction Part I: Use of Texturised Glass Yarn," *Journal of Textile Institute* 36(1995) 96-103.

Hill, B.J., R. McIlhagger, C.M. Harper and W. Wenger, "Woven Integrated Multilayered Structures for Engineering Preforms," *Composites Manufacturing* 5(1994) 25-30.

- Ichihashi, H., H. Hamada, N. Ikuta and Z. Maekawa, "Finite element analysis of woven fabric composites considering interfacial properties," *Composite Interfaces* 2(1994) 81-94.
- Ishikawa, T., and T.W. Chou, "Stiffness and Strength Behavior of Woven Fabric Composites," *Journal of Materials Science* 17(1982), 3211-3220.
- Ishikawa, T., and T.W. Chou, "Elastic Behavior of Woven Hybrid Composites," *Journal of Composite Materials* 16(1982), 2-19.
- Johnson, C., in *Composites*, ASM International, 1993.
- Kageyama, K., T. Kobayashi and T.W. Chou, "Analytical Compliance Method for Mode I Interlaminar Fracture Toughness Testing of Composites," *Composites* 18(1987) 393-399.
- Karbhari, V.M. and S.G. Slotte, "Effect of Fiber Architecture on Manufacturability and Crush Performance of a Stiffened Plate Type RTM Structure," *Composite Structures* 26(1993) 83-93.
- Keefe, M., D.C. Edwards and J. Yang, "Solid Modeling of Yarn and Fiber Assemblies," *Journal of Textile Institute* 33(1992) 185-196.
- Keefe, M., "Solid Modeling Applied to Fibrous Assemblies Part I: Twisted Yarns," *Journal of Textile Institute* 35 (1994) 338-349.
- Keefe, M., "Solid Modeling Applied to Fibrous Assemblies Part II: Woven Fabric," *Journal of Textile Institute* 35(1994) 350-358.
- Kendall, K.N., C.D. Rudd, M.J. Owen and V. Middleton, "Characterisation of the Resin Transfer Moulding Process," *Composites Manufacturing* 3(1992) 235-249.
- Khanh, T.V. and B. Liu, "Prediction of Fibre Rearrangement and Thermal expansion behaviour of deformed woven-formed laminates," *Composites Science and Technology* 53(1995) 183-191.
- Kikuchi, A., E. Higuerey and J. Coulter, "An Experimental Investigation of Resin Flow Sensing During Molding Processes," *Journal of Engineering Materials and Technology* 117(1995) 86-93.
- Kranbuehl, D., D. Eichinger, T. Hamilton and R. Clark, "In-Situ Monitoring of the Resin Transfer Molding Impregnation and Cure Process," *Polymer Science and Engineering* 31(1991) 56-60.
- Lam, R.C. and J.L. Kardos, "The Permeability and Compressibility of Aligned and Cross-Plied Carbon Fiber Beds During Processing of Composites," *Polymer Engineering and Science* 31(1991) 1064-71.
- Larson, B.K. and L.T. Drzal, "Glass Fibre Sizing/Matrix Interphase Formation in Liquid Composite Moulding: Effects on Fibre/Matrix Adhesion and Mechanical Properties," *Composites* 25(1994) 711-721.
- Laroche, D. and T. Vu-Khanh, "Forming of Woven Fabric Composites," *Journal of Composite Materials* 28(1994) 1825-39.

Robertson, R.E., E.S. Hsiue and G.S.Y. Yeh, "Continuous Fiber Rearrangements During the Molding of Fiber Composites. I. Flat Cloth to a Hemisphere," *Polymer Composites* 2(1981) 126-131.

Shembekar, P.S. and N.K. Naik, "Elastic Behaviour of Woven Fabric Composites:II - Laminate Analysis," *Journal of Composite Materials* 26(1992) 2226-2245.

Skartsis, L., J.L. Kardos and B. Khomami, "Resin Flow Through Fiber Beds During Composites Manufacturing Processes. Part I: Review of Newtonian Flow Through Fiber Beds," *Polymer Engineering and Science* 32(1991) 221-230.

Skartsis, L., J.L. Kardos and B. Khomami, "Resin Flow Through Fiber Beds During Composites Manufacturing Processes. Part II: Numerical and Experimental Studies of Newtonian Flow Through Ideal and Actual Fiber Beds," *Polymer Engineering and Science* 32(1991) 230-239.

Skartsis, L., J.L. Kardos and B. Khomami, "Polymeric Flow Through Fibrous Media," *Journal of Rheology* 36(1992) 589-620.

Smithgall, D.H., R.E. Frazee Jr., "Characterization of the Preform Stretching Process," *Journal of Lightwave Technology* 12(1987) 1755-62.

Steenkamer, D.A., D.J. Wilkins, and V.M. Karbhari, "The influence of Preform Joints on the Processing of RTM Composites," *Composites Manufacturing* 6(1995) 23-34.

Suemasu, H., K. Friedrich and M. Hou, "On Deformation of Woven Fabric-Reinforced Thermoplastic Composites During Stamp-Forming," *Composites Manufacturing* 5(1994) 31-39.

Trochu, F., R. Gauvin, and D.M. Gao, "Numerical Analysis of the Resin Transfer Molding Process by the Finite Element Method," *Advances in Polymer Technology* 12(1993) 329-342.

Um, M.K. and W.I. Lee, "A Study on the Mold Filling Process in Resin Transfer Molding," *Polymer Engineering and Science* 31(1991) 765-771.

Um, M.K. and W.I. Lee, "Numerical Simulation of Resin Transfer Molding Process Using Boundary Element Method," [Proceedings of the] 35th International SAMPE Symposium, April, 1990 1905-1916.

Verheus, A.S. and J.H.A. Peeters, "The Role of Reinforcement Permeability in Resin Transfer Moulding," *Composites Manufacturing* 4(1993) 33-38.

Vu-Khanh, T. and B. Liu, "Prediction of Fibre Rearrangement and Thermal Expansion Behaviour of Deformed Woven-Fabric Laminates," *Composites Science and Technology* 53(1995) 183-191.

Walsh, S.M. and M. Charmchi, "Free Surface Flow Observations in the Resin Transfer Molding Process," *Heat & Mass Transfer in Materials Processing and Manufacturing* 261(1993) 147-156.

Wang, Y. and D. Zhao, "Characterization of Interlaminar Fracture Behavior of Woven Fabric Reinforced Polymeric Composites," *Composites* 26(1995) 115-124.

Whitcomb, J., G. Kondagunta, and K. Woo, "Boundary Effects in Woven Composites," *Journal of Composite Materials* 29(1995) 507-524.

Whitney, T.J. and T.W. Chou, "Modeling of 3-D Angle Interlock Textile Structural Composites," *Journal of Composite Materials* 23(1989) 890-911.

Yao, L.N. and T.W. Chou, "3-Dimensional Analysis of Composite Residual Stresses Due to Twisted Fiber Bundles," *Science in China* 34(1991) 467-478.

Young, W.B., "Three-Dimensional Nonisothermal Mold Filling Simulations in Resin Transfer Molding," *Polymer Composites* 15(1994) 118-127.

Yu, J.Z., Z. Cai and F.K. Ko, "Formability of Textile Preforms for Composite Applications; Part 1: Characterization Experiments," *Composites Manufacturing* 5(1994) 113-122.

THERMOELASTIC EFFECTS: AVERAGE IN-PLANE PROPERTIES

I. MOSAIC MODEL

In the mosaic model the average strains and curvatures of a one-dimensional strip of width a along the fill or warp direction due to a uniform temperature change, ΔT , can be expressed in the following forms:

$$\begin{aligned} \epsilon_i^o &= 1/n_g a \int_0^{n_g a} \Delta T \bar{a}_i^*(\xi) d\xi = \Delta T \bar{a}_i^* \quad (i=1,2) \\ \bar{k}_i^o &= 1/n_g a \int_0^{n_g a} \Delta T \bar{b}_i^*(\xi) d\xi = \Delta T \frac{n_g - 2}{n_g} \bar{b}_i^* \quad (i=1,2) \end{aligned} \quad \text{---1}$$

From the above eqns the average thermal expansion and thermal bending coefficients for the mosaic model are given by

$$\begin{aligned} \bar{a}_i^* &= \bar{a}_i^* \\ \bar{b}_i^* &= \left(1 - \frac{2}{n_g}\right) \bar{b}_i^* \end{aligned} \quad \text{---2}$$

II. THE CRIMP MODEL

By following the same method we get the crimp model:

$$\begin{aligned} \bar{a}_i^{*c} &= \left(1 - \frac{2a_g}{n_g a}\right) \bar{a}_i^* + \frac{2}{n_g a} \int_0^{a_g} \bar{a}_i^*(\xi) d\xi \\ \bar{b}_i^{*c} &= \left(1 - \frac{2}{n_g}\right) \bar{b}_i^* + \frac{2}{n_g a} \int_0^{a_g} \bar{b}_i^*(\xi) d\xi \end{aligned} \quad \text{---3}$$

The superscript C signifies the crimp model.

For the in plane thermal expansion coefficient, it is necessary to evaluate the integration in eqn 3. first $A_i(\xi)$ and $B_i(\xi)$ are evaluated from eqns for $0 \leq \xi \leq a/2$ and the results are

$$\begin{aligned} \bar{A}_i(\xi) &= q_i^M (h_1(\xi) - h_2(\xi) + h - h_i/2) + g_i^F(\theta) h_i/2 + q_i^W (h_2(\xi) - h_1(\xi)) \\ \bar{B}_i(\xi) &= (1/2) q_i^F(\theta) (h_1(\xi) - h_i/4) h_i + q_i^W (h_2(\xi) - h_1(\xi)) h_i/4 \end{aligned} \quad \text{---4}$$

Next q_i is determined and the off-axis thermal expansion coefficients $\alpha_i^F(\theta)$ are given by

$$\begin{aligned}\alpha_1^F(\theta) &= \cos^2 \theta \alpha_L^F + \sin^2 \theta \alpha_T^F \\ \alpha_2^F(\theta) &= \alpha_T^F \\ \alpha_6^F(\theta) &= 0\end{aligned}\quad \text{---5}$$

III. THE BRIDGING MODEL

For the thermal property analysis, assuming no external loading, the equilibrium of the bridging regions requires

$$a \begin{Bmatrix} N_i^C \\ M_i^C \end{Bmatrix} + (\sqrt{n_s} - 1) a \begin{Bmatrix} N_i \\ M_i \end{Bmatrix} = 0$$

where the superscript C again denotes the crimped region, and N_i and M_i without superscripts are for the cross-ply laminate. we define

$$\begin{aligned}F_i^{oC} &= \bar{E}_i^o \\ k_i^{oC} &= \bar{k}_i^o\end{aligned}$$

Substituting into the previous eqn we have

$$\left(\begin{bmatrix} A_{ij}^C & B_{ij}^C \\ B_{ij}^C & D_{ij}^C \end{bmatrix} + (\sqrt{n_s} - 1) \begin{bmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{bmatrix} \right) \begin{Bmatrix} \bar{\epsilon}_j^o \\ \bar{k}_j^o \end{Bmatrix} = \Delta T \left[\begin{Bmatrix} \bar{A}_i^C \\ \bar{B}_i^C \end{Bmatrix} + (\sqrt{n_s} - 1) \begin{Bmatrix} \bar{A}_i \\ \bar{B}_i \end{Bmatrix} \right]$$

The quantities on the left hand side of the above eqn can be related to the average elastic stiffness in the bridging regions as

$$\begin{bmatrix} A_{ij}^C & B_{ij}^C \\ B_{ij}^C & D_{ij}^C \end{bmatrix} + (\sqrt{n_s} - 1) \begin{bmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{bmatrix} = \sqrt{n_s} \begin{bmatrix} \bar{A}_{ij} & \bar{B}_{ij} \\ \bar{B}_{ij} & \bar{D}_{ij} \end{bmatrix}$$

Hence the eqn becomes

$$\begin{Bmatrix} \varepsilon_i^o \\ \bar{k}_i \end{Bmatrix} = \Delta T \begin{bmatrix} \bar{a}_{ij}^* & \bar{b}_{ij}^* \\ \bar{b}_{ij}^* & \bar{d}_{ij}^* \end{bmatrix} \begin{Bmatrix} \frac{1}{n_s} \left\{ \tilde{A}_j^c \right\} \\ \frac{1}{\tilde{B}_j^c} \left\{ \tilde{B}_j \right\} \end{Bmatrix} + \left(1 - \frac{1}{n_s} \right) \begin{Bmatrix} \tilde{A}_i \\ \tilde{B}_i \end{Bmatrix}$$

The quantities in parenthesis can be regarded as average values for the bridging regions and hence, they are denoted by $\bar{\tilde{A}}_j$ and $\bar{\tilde{B}}_j$. Thus we obtain

$$\begin{Bmatrix} \bar{a}_i^* \\ \bar{b}_i^* \end{Bmatrix} = \begin{bmatrix} \bar{a}_{ij}^* & \bar{b}_{ij}^* \\ \bar{b}_{ij}^* & \bar{d}_{ij}^* \end{bmatrix} \begin{Bmatrix} \bar{\tilde{A}}_j \\ \bar{\tilde{B}}_j \end{Bmatrix}$$

Finally, the whole satin composite can be regarded as a linkage of the regions. The average strain and curvature for the entire model are given by

$$\begin{aligned} \begin{Bmatrix} \bar{a}_i^* \\ \bar{k}_i^* \end{Bmatrix} &= \frac{1}{\sqrt{n_s}} \begin{Bmatrix} 2 \left\{ \tilde{\varepsilon}_i^o \right\} \\ \left\{ \tilde{k}_i \right\} \end{Bmatrix} + \left(\sqrt{n_s} \right) \begin{Bmatrix} \varepsilon_i^o \\ k_i \end{Bmatrix} \\ &= \Delta T \begin{Bmatrix} \frac{2}{n_s} \left\{ \tilde{a}_i^* \right\} \\ \left\{ \tilde{b}_i^* \right\} \end{Bmatrix} + \left(1 - \frac{2}{\sqrt{n_s}} \right) \begin{Bmatrix} \tilde{a}_i^* \\ \tilde{b}_i^* \end{Bmatrix} \end{aligned}$$

The above eqn implies

$$\begin{Bmatrix} \bar{a}_i^* \\ \bar{b}_i^* \end{Bmatrix} = \frac{2}{n_s} \begin{Bmatrix} \tilde{a}_i^* \\ \tilde{b}_i^* \end{Bmatrix} + \left(1 - \frac{2}{\sqrt{n_s}} \right) \begin{Bmatrix} \tilde{a}_i^* \\ \tilde{b}_i^* \end{Bmatrix}$$

for the thermal expansion and thermal bending coefficients of the satin composites.

AVERAGE IN-PLANE COMPLIANCE CONSTANTS

I. THE MOSAIC MODEL

The constitutive equations for the Mosaic model is

$$\begin{bmatrix} N_1 \\ N_2 \\ N_6 \end{bmatrix} = \begin{bmatrix} (E_1 + E_2)h/2D_v & \nu_{12}E_2h/D_v & 0 \\ \nu_{12}E_2h/D_v & (E_1 + E_2)h/2D_v & 0 \\ 0 & 0 & G_{12}h \end{bmatrix} \begin{bmatrix} \epsilon_1^o \\ \epsilon_2^o \\ \epsilon_6^o \end{bmatrix} + \begin{bmatrix} (E_1 - E_2)h^2/8D_v & 0 & 0 \\ 0 & -(E_1 - E_2)h^2/8D_v & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \kappa_1 \\ \kappa_2 \\ \kappa_6 \end{bmatrix}$$

$$\begin{bmatrix} M_1 \\ M_2 \\ M_6 \end{bmatrix} = \begin{bmatrix} (E_1 - E_2)h^3/8D_v & 0 & 0 \\ 0 & -(E_1 - E_2)h^3/8D_v & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \epsilon_1^o \\ \epsilon_2^o \\ \epsilon_6^o \end{bmatrix} + \begin{bmatrix} (E_1 + E_2)h^3/24D_v & \nu_{12}E_2h^3/12D_v & 0 \\ \nu_{12}E_2h^3/12D_v & (E_1 + E_2)h^3/24D_v & 0 \\ 0 & 0 & G_{12}h^3/12 \end{bmatrix} \begin{bmatrix} \kappa_1 \\ \kappa_2 \\ \kappa_6 \end{bmatrix}$$

where $D_v = 1 - \nu_{12}\nu_{21}$ and the terms in the 3 x 3 matrices give the non vanishing stiffness constants in terms of elastic constants. The compliance constants can be found out by inverting the above equation. If a_{ij}^* , b_{ij}^* and d_{ij}^* are the compliance constants then the average compliance constants are given as follows:

$$\bar{a}_{ij}^* = a_{ij}^*$$

$$\bar{b}_{ij}^* = \left(1 - \frac{2}{n_g}\right) b_{ij}^{*L}$$

$$\bar{d}_{ij}^* = d_{ij}^*$$

II. THE CRIMP MODEL

The average in-plane compliance of the crimp model under a uniformly applied in-plane stress resultant is defined by

$$\bar{a}_{ij}^C = 2/n_g a \int_0^{n_g u/2} a_{ij}^*(x) dx \Rightarrow \bar{a}_{ij}^C = (1 - 2a_u/n_g a) a_{ij}^* + 2/n_g a \int_{a_0}^{u_2} a_{ij}^*(x) dx$$

where superscript C signifies the crimp model.

$\overline{b_{ij}^{*c}}$ and $\overline{d_{ij}^{*c}}$ are obtained in a similar manner.

$$\overline{b_{ij}^{*c}} = (1 - 2/n_s) b_{ij}^* + 2/n_s a \int_{a_1}^{a_2} b_{ij}^*(x) dx$$

$$\overline{d_{ij}^{*c}} = (1 - 2a_u/n_s a) d_{ij}^* + 2/n_s a \int_{a_1}^{a_2} d_{ij}^*(x) dx$$

III. THE BRIDGING MODEL

The bridging model is used for the analysis of satin composites. This model is valid only for satin weaves where $n_s \geq 4$.

The average stiffness constants are

$$\overline{A_{ij}} = 1/\sqrt{n_s} \left[(\sqrt{n_s} - 1) A_{ij} + \overline{A_{ij}^c} \right]$$

$$\overline{B_{ij}} = 1/\sqrt{n_s} (\sqrt{n_s} - 1) B_{ij}$$

---1

$$\overline{D_{ij}} = 1/\sqrt{n_s} \left[(\sqrt{n_s} - 1) D_{ij} + \overline{D_{ij}^c} \right]$$

$\overline{A_{ij}^{*c}}$ and $\overline{D_{ij}^{*c}}$ for the undulated portion are obtained from $\overline{a_{ij}^{*c}}$ and $\overline{d_{ij}^{*c}}$ and $\overline{b_{ij}^{*c}} = 0$.

A_{ij} , B_{ij} and D_{ij} are given by the standard formulas.

The average compliance constants are derived as

$$\overline{a_{ij}^{*s}} = 1/\sqrt{n_s} \left[2\overline{a_{ij}^*} + (\sqrt{n_s} - 2) a_{ij}^* \right]$$

$$\overline{b_{ij}^{*s}} = 1/\sqrt{n_s} \left[2\overline{b_{ij}^*} + (\sqrt{n_s} - 2) b_{ij}^* \right]$$

---2

$$\overline{d_{ij}^{*s}} = 1/\sqrt{n_s} \left[2\overline{d_{ij}^*} + (\sqrt{n_s} - 2) d_{ij}^* \right]$$

where $\overline{a_{ij}^*}$, $\overline{b_{ij}^*}$ and $\overline{d_{ij}^*}$ are determined by inverting the eqn 1 and the quantities with superscript S denote properties of the entire satin plane. Finally, $\overline{A_{ij}^s}$, $\overline{B_{ij}^s}$ and $\overline{D_{ij}^s}$ can be obtained by inverting eqn 2.

LOCAL IN-PLANE COMPLIANCES

I. The Crimp Model

The crimp model, which is a one-dimensional approximation and takes into account fiber continuity and undulation, is particularly suited for predicting elastic properties of plain weave composites.

Fig 1. Fiber Crimp model

The undulation shape is defined by the parameters $h_1(x)$, $h_2(x)$, and a_u . To simulate the actual configuration, the following form of crimp is assumed for the fill yarn

$$h_1(x) = \begin{cases} 0 & (0 \leq x \leq a_0) \\ \left[1 + \sin\left\{ \frac{(x - a/2)\pi}{a_u} \right\} \right] h_i / 4 & (a_0 \leq x \leq a_2) \\ h_i / 2 & (a_2 \leq x \leq n_2 a/2) \end{cases} \quad \text{---1}$$

The sectional shape of the warp yarn is expressed by

$$h_2(x) = \begin{cases} h_i / 2 & (0 \leq x \leq a_0) \\ [1 - \sin\{(x - a/2)\pi / a_u\}] h_i / 4 & (a_0 \leq x \leq a/2) \\ -[1 + \sin\{(x - a/2)\pi / a_u\}] h_i / 4 & (a/2 \leq x \leq a_2) \\ -h_i / 2 & (a_2 \leq x \leq n_2 a/2) \end{cases} \quad \text{---2}$$

Thus A_{ij} , B_{ij} , and D_{ij} are expressed as functions of x ($0 \leq x \leq a/2$) by

$$\begin{aligned}
 A_{ij}(x) &= \int_{-h/2}^{h_1(x)-h_i/2} Q_{ij}^M dz + \int_{h_1(x)-h_i/2}^{h_1(x)} Q_{ij}^F(\theta) dz + \int_{h_1(x)}^{h_2(x)} Q_{ij}^W dz + \int_{h_2(x)}^{h/2} Q_{ij}^M dz \\
 &= Q_{ij}^M (h_1(x) - h_2(x) + h - h_i/2) + Q_{ij}^F(\theta) h_i/2 + Q_{ij}^W (h_2(x) - h_1(x)) \\
 B_{ij}(x) &= 1/2 Q_{ij}^F(\theta) [h_1(x) - h_i/4] h_i + 1/4 Q_{ij}^W [h_2(x) - h_1(x)] h_i \\
 D_{ij}(x) &= 1/3 Q_{ij}^M \{ [h_1(x) - h_i/2]^3 - h_2(x)^3 + h^3/4 \} \\
 &\quad + 1/3 Q_{ij}^F(\theta) [h_i^3/8 - 3h_i^2 h_1(x)/4 + 3h_i h_1^2(x)/4 + 3h_i h_1^2(x)/2] \\
 &\quad + 1/3 Q_{ij}^W [h_2(x)^3 - h_1(x)^3] \quad \text{---3}
 \end{aligned}$$

Similarly for $a/2 \leq x \leq n_g a/2$, we can write expressions for A_{ij} , B_{ij} and D_{ij} .

The local stiffness of the fill, $Q_{ij}(\theta)$, in the above equations is calculated as a function of the local off-axis angle, $\theta(x)$ which is defined as

$$\theta(x) = \arctan(dh_1(x)/dx)$$

If we consider a fill yarn of parallel fibers where 1 denotes the fiber direction; the 2 and 3 directions are perpendicular to the fiber and define the transversely isotropic plane. The elastic constants of the fill yarn with respect to the xyz axis can be defined.

$$\begin{aligned}
 E_x^F(\theta) &= 1/[l_\theta^4/E_1 + (1/G_{13} - 2\nu_{31}/E_1)l_\theta^2 m_\theta^2 + m_\theta^4/E_3] \\
 E_y^F(\theta) &= E_2 = E_3 \\
 G_{xy}^F(\theta) &= 1/[l_\theta^2/G_{12} + m_\theta^2/G_{23}] \\
 \nu_{yx}^F(\theta) &= \nu_{31} l_\theta^2 + \nu_{23} m_\theta^2 \\
 &\text{where } l_\theta = \cos \theta \text{ and } m_\theta = \sin \theta. \quad \text{---4}
 \end{aligned}$$

Thus the local stiffness constants of the undulated portion of the fill yarn are given as functions of fiber orientation θ

$$Q_{ij}^F(\theta) = \begin{bmatrix} E_x^F(\theta)/D_v & E_y^F(\theta)v_{yx}^F(\theta)/D_v & 0 \\ E_x^F(\theta)v_{yx}^F(\theta)/D_v & E_y^F(\theta)/D_v & 0 \\ 0 & 0 & G_{xy}^F(\theta) \end{bmatrix}$$

where $D_v = 1 - (v_{yx}^F(\theta))^2 E_x^F(\theta)/E_y^F(\theta)$

By substituting the above into the previous equation the local plate stiffness constants can be evaluated.

Analysis of Composite Structures Manufactured by Resin Transfer Mold (RTM) Processing

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**IMPreS Program
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September 14, 1995**

OUTLINE

- I. Introduction**
- II. Constituent Modeling: fibers, fabrics, preforms**
- III. Structural Modeling**
- IV. Conclusions/Recommendations**

Miscellaneous Notes

- Full literature review documented in report--see Steve Burchett.
- References here are listed in the report.
- Equations for fabric models available; short report sent to Steve.

(yes, I did dump all of this on poor Steve--AM)

Introduction: Structures Produced by RTM Processing

A high-speed resin transfer molding operation (Johnson, 1993)

Liquid Molding Processes for Composites

- versatile & economical
- fabric (nonwoven or woven) reinforcements, particulates, short fibers

Resin Transfer Molding

- liquid molding, closed mold
- generally uses thermosetting resins (some thermoplastics under development)
- fabric "preforms," flat panels (stamped to net shape) or joined sections

Introduction: Components of Analysis

Structural Analysis and Design

- requires combined analyses:
 - constituents (matrix, reinforcement)
 - arrangement (weave geometry, structure geometry)
 - processing (temperature, pressure, degree-of-cure)
- MAIN COMPONENTS
 - elastic properties of fabric microstructures
 - preform structural response
 - composite modeling, incorporating process modeling

Some available microstructures (Chou, 1989)

Constituent Modeling: the Reinforcement Phase

Rule of Mixtures (ROM) Analyses

- implicitly, ALWAYS include assumptions about arrangement
simplest example - series and parallel rules (resistance or stiffness)

- must first know each constituent's properties, then use weighted average
- no-brainer for aligned fibers (see above picture), but can be complicated for woven structures
 - coupling effects due to interlocking
 - must invoke micromechanics for the *reinforcement* phase, and again for the *composite*

Constituent Modeling: from Fibers to Fabrics to Preforms

Fibers

- combined in "tows" of 1000-5000 aligned fibers
- engineering fibers: glass, carbon, aramid

Textiles

- nonwovens ("spray-down" of short fibers onto screens) or wovens
- 3D wovens or laminated 2D wovens (as in tape laydown)

Preforms

- stamping of flat sheets into complex geometries
- spray-down of short fibers onto complex mold surface directly, or laying down successive layers, covering joints as necessary
- stitching of fabrics to join flat sections
- filament winding of fibers to near net-shape preforms

Constituent Models: General Solutions

Two Main Bodies of Work:

1) Fabric to Preform to Composite

WANT TO KNOW

- "drapability"--will wrinkles form?
- alteration of microstructures--will gaps form due to high shear?
- Ultimately, how does this affect manufacturability
(impregnation of the deformed fabric microstructure with resin)

2) (Flat) Composite Fabric Approach (then do complex analyses with rotation of composite properties, neglecting laydown effects on microstructure)

WANT TO KNOW

- how matrix and fiber properties combine to give local fabric properties
- how to get average properties in the fabric from the local properties

WHAT REALLY HAPPENS:

The conformation of the dry fabric to the mold surface changes both the structural properties and the processing properties (local permeability) of the preform. Use of the flat fabric composite properties both in processing and structural analysis is an approximation of the real properties.

Constituent Modeling: Fabric Composite Models

Main Ideas:

- **Use laminated plate theory in a piecewise fashion to characterize the fabric's unit cell, then use an average value to get the continuum constants.**
- **Incorporate coupling effects for weaves where it is important (e.g. not as important in plain weaves as in satin weaves).**

Constituent Modeling: Dry Fabric Work

Fiber Modeling--Classic Work: Peirce(1937)

- first model of contacting fibers
- recent application: deformation of fabrics

Fabric Modeling--Textiles

- draping (Robertson, 1981-4; Van West, 1990; Aono, 1994)
over arbitrary surfaces of dry fabrics

Draping over a rounded cone
(Robertson, 1984)

Draping over an arbitrary surface
(Van West, 1990)

Constituent Modeling: Fabric Composite Models

[equations available for local and continuum analyses--Steve Burchett has them...]

1) Mosaic Model (pretty good for plain weaves; has been applied to other types)

2) Crimp Model (basis for bridging model; good for satin weaves)

3) Bridging Model(extension of (2); incorporates interlacing effects)

(all from Chou, 1989)

Structural Modeling: Application of Micromechanical Models

Micromechanical Models Give:

- **local and continuum properties of fabric composites (see Steve for equations)--can plug directly into continuum FEM code with appropriate calculation of stiffness coefficients (IMPORTANT--select microstructural model based on fabric geometry)**
- **prediction of fabric drapability in CURVED structures--can select deformable fabrics for complicated component geometries**

To apply the models, must:

- **understand how local microstructure changes with laydown**
- **understand how local microstructure affects net structural properties**
- **understand how local microstructure affects net processing properties**

**THERE ARE SEVERAL IMPORTANT FLUID-STRUCTURE INTERACTION
PROBLEMS IN ANALYSIS OF CURVED STRUCTURES**

Structural Modeling: Fluid Structure Interaction Problems Addressed

- fiber tow wetting
 - selection of sizings (Drzal et al., 1985-94; Bayramli and Powell, 1992; Chan and Morgan, 1993; Ghali et al. 1994)
 - heat and mass transfer during "wicking" (Ghali et al., 1995)
- permeability determination based on fiber architecture (Adams and Rebenfeld, 1991; Dabe, 1990; Verheus and Peeters, 1993)

Structural Modeling: Properties Addressed

There are several areas of current interest in the structural modelling of curved components...topics include

- Thermoelastic effects
 - fiber tow level due to twisted yarns (Yao and Chou, 1991)
 - fabric level (Ishikawa and Chou, 1982; Ganesh and Naik, 1994)--see equations
- Edge effects in fabrics (Whitcomb, 1995)
- Fracture toughness of fabrics (Guenon, 1989; Wand and Zhao, 1995)
- Analysis of joints (Lin and Tsai, 1995)

Conclusions and Recommendations

Structural Analysis

SHORT TERM:

- select ROM micromechanical approach based on fabric architecture
- enter stiffness coefficients into continuum FEM code

LONG TERM (research area):

- incorporate microstructural models of fabric geometries into mesh description
- use stiffness coefficients based on fabric deformation due to conformation with the mold
- select local permeability coefficients based upon fabric deformation upon conformation

APPENDIX E—COMPOSITE MODEL EVALUATION - FAILURE MECHANISMS AND MICROMECHANICS

Charts and text provided by Khanh Trinh.

date: October 19, 1995

to: Linda Domeier, Org. 8713, MS 9404

from: Khanh Trinh, Org. 8742, MS 9043

subject: Materials for IMPReS report.

This memo presents a summary of the mechanical modeling study performed in support of the IMPReS program. I have also attached to this memo a copy of my wrap-up meeting vu-graphs, and a copy of the paper that Wei-yang Lu, Org. 8745, and I presented at the 10th International Conference on Composite Materials (ICCM-10).

There were two major efforts in the mechanical modeling study in support of the IMPReS program: the development of a damage material model and the investigation of existing micromechanic models for composite materials. The following two sections describe these two efforts respectively.

Effort one: Damage material model for composite materials

The structural performance of a part under actual service loads can be determined either experimentally using laboratory testings or analytically using a mathematical model. Since testing can be very costly, it is desirable to have an analytical method that can predict the part performance with reasonable accuracy at a lower cost. The finite element method is an analytical method that is widely used to predict structural performance of parts with complex geometries, loadings, and material behaviors. We have commercial and Sandia in-house finite element codes that can model complex geometries and loadings. However, existing material models can not predict failure responses of composite parts that will be produced by the IMPReS program. The goal of effort one was to develop such a damage material model.

The damage material model was developed to be used with the commercial finite element code ABAQUS based on the desire of the IMPReS working group to work with commercial codes. ABAQUS is a popular code that is widely used both inside and outside of Sandia. I also have plan to implement this model into the PRONTO code in the future.

ABAQUS and other finite element codes used at Sandia have built-in material model that can only model undamaged layer composites. The new model adds two important features required for modeling damages and failures: failure criteria to predict the on-set of various material failures, and degradation rules to model the loss of stiffness and strength due to the failures. These two features allow an analysis to simulate the progressive damage nature of composite structures from the first damage to the

ultimate laminate failure; the analysis can predict the extent of damages in the material at any level of loading.

Failures of composite materials are complex. There are many failure modes: matrix cracking of the resin, failure of bonds between fibers and the resin (fiber/matrix shear-out), fiber tensile breakage, fiber buckling, delamination of layered composites, etc. Different failure mode causes different degradation to the material. For example, matrix cracking causes very little stiffness degradation, and frequently occurred well below the design load in practice. On the other hand, fiber failure causes great stiffness degradation that usually leads to total material failure. Some failure modes are relatively simple to implement, others are not. The developed model included five failure modes: matrix cracking, tensile fiber/matrix shear-out, compressive fiber/matrix shear-out, matrix compression, and fiber breakage. Basically, these are relatively simple in-plane failure modes that were thought to be important for the IMPReS program. The new model does not include out-of-plane failure modes such as delamination.

For a part produced using the RTM method, we may be interested in the strength of the cured resin system (matrix cracking and matrix compression), the strength of the reinforcement system (fiber breakage), the bonds between the resin and the fibers (tensile and compressive fiber/matrix shear-out), and the void content of the finished part (related to matrix cracking). The new model uses a crack density (number of crack per inch) as a state variable to track the extent of damages for the matrix cracking failure mode. This crack density state variable may be used as initial state of the material to account for voids created by the manufacturing process.

The developed model adopted failure criteria and degradation rules recently proposed by a group at Stanford University led by Professor Fu-kuo Chang. Significant changes in the degradation rules and a new numerical procedure was implemented to overcome convergence problems in ABAQUS. Convergence problems are serious. They have limited the uses of progressive failure modeling for composite materials.

The model was validated using test data of uniaxially loaded composite coupons with and without slits. These coupons were laminated composites produced using the traditional hand lay-up and autoclave cured method. Test data for composites produced using the RTM method was not available. Comparisons between experimental results and ABAQUS finite element results showed that the developed composite material model works well. More details about the model and the experimental validations can be found in the attached paper, which Wei-yang Lu, Org. 8745, and I recently presented at the ICCM-10 conference.

In summary, I have developed a composite material damage model that can be used with the commercial finite element code ABAQUS to predict responses of composite structures. This model was validated with experimental results.

Effort two: Micromechanic models for composite materials

Micromechanic models predict mechanical properties of composite materials from properties of the constituents. The goal of effort two was to examine existing micromechanic models and determine their applicability to the IMPReS program. In this effort, Jeff Eldredge, a co-op student from Cornell University, and I surveyed some journal papers and some books. We also talked to some industry and academia people. Major findings are summarized below.

Micromechanic models are not trusted and not used for design purposes. These models are simply not accurate enough. The standard in industry is to obtain composite material properties from laboratory measurements. Micromechanic models are used by material engineers for guidance on material improvement purposes.

We can categorize existing micromechanic models into three groups: (1) strength of materials, (2) theory of elasticity, and (3) empirical equations. The strength of material group, which uses simplified mechanical model, has simple equations and requires only basic data such as constituent properties and volume fractions. The rule of mixtures is a micromechanic model from this group. The theory of elasticity group, which uses much more complex mathematical models, has more complex equations and requires more data than group 1. The best known model in group 2 is the Halpin-Tsai model. Models in the empirical group requires lots of existing data, and probably will not be applicable to the IMPReS program.

Besides the lack of accuracy, there are other limitations on micromechanic models. Not all properties can be predicted, and some properties can be predicted more accurate than others. For example, moduli and Poisson's ratios can be predicted much more accurate than strengths. Furthermore, there are restrictions on the type of composite materials that can be treated with micromechanic models. These restrictions came from basic assumptions made by most models. Two of these basic assumptions are that the lamina is macroscopically homogeneous, and that the fibers are regularly spaced and perfectly aligned. These two assumptions limit the uses of micromechanic models to directional lamina (unidirectional or fabric). One must modify existing models (adding fudge factors) to work with less structured composite materials such as lamina with continuous, but not aligned fibers. The lamina with the A-glass mat preform fabricated by Tom Bennet is such a lamina.

For structured composite laminates, I recommend the rule of mixtures model for the IMPReS program because this model is simple to use, requires only basic data, and is probably just as accurate as other more complex model.

Copy without attachments to:

MS 0443 Steve Burchett, 1517
MS 9404 Craig Henderson, 8713
MS 0367 Greg Jamison, 1812
MS 0367 Cliff Renschler, 1812
MS 9402 Jay Spingarn, 8714
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Mechanical Modeling IMPreS Wrap-up Meeting 9/14/95

**Khanh Trinh
Orgn 8742, Structural Mechanics Department.**

Accomplishments

- Developed a material model that can be used by the commercial finite element code ABAQUS to predict structural damages and failures in composite materials.
- Investigated techniques to obtain mechanical properties of composites from properties of constituents and manufacturing data.

Measuring the structural quality of an RTM part:

1. Direct method: subject the part to actual service loads and measure its performance directly.
 - Experimentally
 - Analytically: finite element method with an appropriate material model.
2. Indirect method: measure various material properties through-out the part.
 - Many properties are required: Moduli, Poisson's ratios, strengths, void contents, etc.
 - Spatial variations of material properties may be large. If true, the ultimate performance of the part may be difficult to deduce.
 - Provides more data than the direct method on the performance of the manufacturing process.

Overview of the material model

- Developed to be used with the commercial finite element code ABAQUS (both implicit and explicit version). A modified version will be implemented into the PRONTO codes.
- A progressive damage model: it predicts failures and material degradations at the ply level.
 - Predicts matrix cracking failures before 1st ply failure (fiber failure).
 - Allows analyses to continue up to ultimate structural failure.
- Calculates crack density in each layer, and uses this density as a state variable.
- Accounts for all major in-plane failure modes including matrix cracking and fiber/matrix shear-out. These two failure modes may be important to an RTM parts.

Constitutive relations including failure degradation

$$\begin{pmatrix} \bar{\sigma}_{xx} \\ \bar{\sigma}_{yy} \end{pmatrix} = \begin{pmatrix} Q_{xx}^M(\phi) & Q_{xy}^M(\phi) \\ Q_{yx}^M(\phi) & Q_{yy}^M(\phi) \end{pmatrix} \begin{pmatrix} d_f & 0 \\ 0 & d_f \end{pmatrix} \begin{pmatrix} \bar{\epsilon}_{xx} \\ \bar{\epsilon}_{yy} \end{pmatrix}$$

$$\bar{\gamma}_{xy} = \frac{\bar{\sigma}_{xy}}{G_{xy}^D} + \alpha \left(\frac{\bar{\sigma}_{xy}}{G_{xy}^D} \right)^3$$

$$G_{xy}^D = d_s \, d_f \, G_{xy}^M(\phi)$$

ϕ : matrix crack density, a material state variable.

d_s : degradation factor due to fiber/matrix shear-out.

d_f : degradation factor due to fiber breakage

Hashin failure criteria

Matrix cracking

$$\left(\frac{\bar{\sigma}_{yy}}{Y_t(\phi)} \right)^2 + \left(\frac{\bar{\sigma}_{xy}}{S(\phi)} \right)^2 = e_M^2 \geq 1$$

Fiber/Matrix shear-out

$$\left(\frac{\bar{\sigma}_{xx}}{X_t} \right)^2 + \left(\frac{\bar{\sigma}_{xy}}{S(\phi)} \right)^2 = e_S^2 \geq 1$$

Fiber breakage

$$\left(\frac{\bar{\sigma}_{xx}}{X_t} \right) = e_F \geq 1$$

Y_t : Matrix tensile strength

X_t : Fiber tensile strength

S : Shear strength

Degradation from fiber breakage and fiber/matrix shear-out

$$d_f = e^{-\left(\frac{A_f}{\delta^2}\right)^\beta}$$

A_f : fiber failure area

δ : fiber interaction zone, related to fiber strength distribution

β : fiber degradation rate

$$d_s = e^{-\left(\frac{\phi}{\phi_0}\right)^\eta}$$

ϕ_0 : saturated crack density

η : shear degradation rate

Degradation from matrix cracking

Crack density $\phi = 1/2L$

2D elasticity and fracture mechanic analyses on the representative element estimate stiffness and strength degradations as functions of crack density for each ply .

[(45/-45/45/-45)]s laminate, graphite epoxy

Model can simulate strength reduction due to matrix cracking. Matrix cracking is quantified by crack density ϕ .

{(45/-45/45/-45)}s laminate, graphite epoxy

Ply 1 (45)

MODEL CAN SIMULATE STIFFNESS DEGRADATION
DUE TO MATRIX CRACKING (MEASURED BY ϕ)

Test Program

Material T800/3900-2 Graphite/Toughened Epoxy
provided by Boeing 777 Empennage

Sample geometry

Test Matrix

Panel	Layup %	Geo	#	X-ray
-70	25/50/25	A	3	pretest: all
		B	3	
		C	3	
		D	9	@80 & 90 %
		E	9	of Failure load
-54	10/40/50	B	3	
		D	6	@80 %
		E	6	of Failure load
-76	17/67/17	B	3	
		D	6	@80 %
		E	6	of Failure load

Total 60

Experimental Results of 76E

Far-field stress vs. displacement

Side slit, [45/90/-45/0/-+45/90/+45/0/+45]S

X-RAY OF TESTED COUPON

**Matrix cracking at 90% of failure load
(side slit, case 76E)**

SECTION POINT 1

Ply 45

SECTION POINT 4

Ply 90

ABAQUS PREDICTION
CONTOUR OF CRACK DENSITY, CASE 76E

SECTION POINT 7

Ply -45

SECTION POINT 10

Ply 0

SECTION POINT 1

SDV2	VALUE
	+0.00E-00
	+2.30E-01
	+4.61E-01
	+6.92E-01
	+9.23E-01
	+1.15E+00
	+1.38E+00
	+1.61E+00
	+1.84E+00
	+2.07E+00
	+2.30E+00
	+2.53E+00
	+2.76E+00
	+3.00E+00

MATRIX CRACK

FIBER/MATRIX
SHEAR-OUT

FIBER BREAK

Ply 45

SECTION POINT 4

SDV2	VALUE
	+0.00E-00
	+2.50E-01
	+5.00E-01
	+7.50E-01
	+1.00E+00
	+1.25E+00
	+1.50E+00
	+1.75E+00
	+2.00E+00
	+2.25E+00
	+2.50E+00
	+2.75E+00
	+3.00E+00
	+INFINITY

Ply 90

ABAQUS PREDICTION
CONTOUR OF FAILURE MODE , CASE 76E

SECTION POINT 7

SDV2	VALUE
	+0.00E-00
	+2.50E-01
	+5.00E-01
	+7.50E-01
	+1.00E+00
	+1.25E+00
	+1.50E+00
	+1.75E+00
	+2.00E+00
	+2.25E+00
	+2.50E+00
	+2.75E+00
	+3.00E+00
	+3.00E+00

Ply -45

SECTION POINT 10

SDV2	VALUE
	+0.00E-00
	+2.50E-01
	+5.00E-01
	+7.50E-01
	+1.00E+00
	+1.25E+00
	+1.50E+00
	+1.75E+00
	+2.00E+00
	+2.25E+00
	+2.50E+00
	+2.75E+00
	+3.00E+00
	+3.00E+00

Ply 0

Notch-strength comparison

Specimen	Measured strength (MPa)	Predicted strength (MPa)	Error (%)
70A	915	979	6.9
70B	396	402	1.5
54B	217	207	4.6
76B	291	269	7.4
70C	385	342	11.
70D	386	378	2.1
54D	257	280	8.8
76D	317	336	5.9
70E	219	210	4.2
54E	145	149	2.8
76E	223	241	8.1

This work was presented at the 10th International Conference on Composite Materials (ICCM-10), Whistler, Canada, August 1995.

Obtaining properties of finished RTM parts

Needed properties: Moduli, Poisson's ratios, strengths, porosity, etc.

1. Direct measurement

- Accurate
- Time consuming and costly
- *Standard method for component design purposes*

2. Micromechanics:

- Inaccurate
- Not all required properties can be estimated
- Many models available at various degree of difficulty
- Used by materials engineers for guidance on materials improvement
- *Not trusted by designers for component design purposes*

Micromechanics Models

3 approaches

1. Strength-of-Materials (rule of mixtures)
 - simplest, theory based on vastly simplifying assumptions
 - sufficiently accurate
 - required basic constituents data: moduli, volume fraction, etc.
2. Theory of Elasticity
 - less simplifying assumption, rigorous math
 - 3 subapproaches: bounding, exact and approximate solution
 - generally difficult to use, except for some approximate solution method (best known is the Halpin-Tsai Method)
3. Empirical Equations

Limitations on micromechanics models

Non of the model examined considers the manufacturing process. These models assume required constituents' properties are available.

- Stiffness, strength and volume/weight fraction of the cured resin
- Stiffness, strength and volume/weight fraction of the pre-form

Recommendation

Measured properties should be used for component design purposes. For guidance on material improvement, a simple rule-of-mixtures model is recommended for its simplicity. There are commercial softwares available for this purpose. MIC-MAC from Think Composite (S. Tsai) is one such software.

AN EXPERIMENTAL AND COMPUTATIONAL STUDY OF PROGRESSIVE FAILURE OF LAMINATED COMPOSITES WITH CUTOUTS

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ABSTRACT

A series of experiments was performed to study the progressive failure of T800/3900-2 Graphite/Toughened Epoxy laminates with various lay-ups and cutouts under uniaxial tensile load. Three lay-ups and five specimen geometries, including nonsymmetric specimen geometries such as the side slit and the angle slit, were tested. A material damage accumulation model was implemented into the finite element code ABAQUS and used to predict the failure response of the laminates. This model includes three in-plane failure modes: matrix cracking, fiber/matrix shear out and fiber tensile breakage. The model predicts failure mode, extent of damage and stiffness degradation due to failure, and ultimate failure of the material. Experimental results and model predictions are presented.

INTRODUCTION

Fiber reinforced composites have become an important class of engineering materials. Laminated composites, for example, find wide applications as structural members. It is necessary to characterize the response of composite components under all anticipated loadings. Since holes and slits exist in many structural components, composite laminates with cutouts are a problem of great practical interest. The stress concentration near the cutout frequently causes structural failure. Stress concentrations in composite laminates have been studied extensively for more than two decades [1]. Models are available for predicting the strength of laminates with and without cutout. Most of these models are semi-empirical. They require experimentally determined parameters that are sensitive to laminate geometry and lay-up. This approach for predicting strength is experimentally expensive since a new set of parameters is needed whenever there is a change in the laminate geometry or lay-up.

Another approach for predicting strength in composite laminates is using progressive failure analyses. One popular method using this approach is to simulate a structural problem with the finite element method and predict laminate failures with a material damage model. To be practical, the material model should only use material properties of the lamina (ply) that are independent of laminate geometry and lay-up. Effects of laminate geometry and lay-up should be accounted for by the finite element calculation. This approach is more computationally expensive, but is much more efficient experimentally. The progressive failure analysis approach has attracted much attention because of its non-empirical nature. An example of a material damage model suitable for this approach was recently proposed by Shahid and Chang [2]. This model was shown to match limited experimental data for some cutout geometries such as a center circular hole and a center slit.

This paper presents a combined experimental and computational study of progressive failure in composite laminates with various lay-ups and cutouts under in-plane tensile load. The long term

Table 1. Test summary

Panel ID	Lay-up %	Geometry	X-ray radiography
70	25/50/25 16 plies	A	pre-test
		B	
		C	
		D	pre-test, 80% and 90% of failure load
		E	
54V	10/40/50 20 plies	B	pre-test
		D	pre-test &
		E	90% of failure load
76	17/67/17 24 plies	B	pre-test
		D	pre-test &
		E	90% of failure load

goal of this investigation is to develop a constitutive model for fiber reinforced composites that is suitable for predicting progressive failure of general laminates under general loads.

EXPERIMENTS

A series of experiments was performed to study the progressive failure of T800/3900-2 Graphite/Toughened Epoxy laminates. As shown in Table 1, three lay-ups and five geometries were included. The distribution of ply orientation is indicated as 'x/y/z' in the second column of the table, where x, y and z are percentages of 0, ± 45 and 90 degree plies, respectively. The ply angle is measured counterclockwise from the loading axis that is vertical. Panel 70, [(45/90/-45/0)₂]_s, is quasi-isotropic. Panel 54V, [-45/0/45/90₂/-45/90₂/45/0]_s is dominated by 90 degree ply. Panel 76, [45/90/-45/0/-45/45/90/45/-45/0/45/-45]_s, is dominated by ± 45 degree ply. All three panels have different thickness. The nominal thickness of a ply is 0.188 mm.

Specimen geometries are shown in Figure 1. Geometry A has a uniform gage area. The cutouts in geometry B, C, D and E specimens are circular hole, slit, slant slit, and side slit, respectively. Since we did not repeat the characterization of T800/3900-2 unidirectional laminate, geometries A, B and C specimens were used to verify the model parameters. The cutouts in D and E are not

Figure 1 Sample geometry and setup

symmetric with respect to specimen axes. The angle between the loading axis and the slant slit is 60 degrees, which is not aligned with any fiber direction.

After machining, all samples were examined by using X-ray penetrant-enhanced radiography to ensure they were free of defect. Most samples were loaded monotonically to failure. Some samples were first loaded to 80 or 90 percent of the failure load, then they were unloaded and removed from the loading frame for making X-ray radiographs. These samples were loaded again to failure. Fractured surfaces were examined visually immediately after each test.

It is known that T800/3900-2 laminates behave consistently, and its scatter in experimental data is smaller than many other polymeric composites. Therefore, only three replicas were used in each test condition. Tests were performed on an Instron screw driven system. The extension rate was about 5×10^{-3} mm/s. One biaxial extensometer and one clip-on gage were used to monitor the deformation during loading. The biaxial extensometer has three channels: two independent channels (A and B) for axial strain and one (T) for transverse strain. Gages A and B have the same gage length of 25.4 mm; the gage length of T is adjustable. The clip-on gage (C) was modified to have a long gage length of 96.5 mm. A typical setup of type E specimen is shown in figure 1.

EXPERIMENTAL RESULTS

Verifying the damage accumulation model requires experimental results not only on laminate strength but also on deformation, damage and failure. Only few experiments provide such complete information. The experiments provide data for bench-marking in-plane models and guiding future model development.

DEFORMATION

Load-displacement curves of D and E samples are plotted in Figure 2. The ordinate, far field stress, is the load divided by the original area of the uniform cross-section that does not have a cutout. The abscissa is the measured displacement normalized by its gage length. Most of the plots show only the results of a typical specimen. The plot of 76E has the results of all three specimens on it to demonstrate the small experimental scatter of these laminates.

During a test, there was occasionally click noise from the sample. When the loading was greater than 80 percent of the failure load, one or two loud pop sounds could be heard; then finally came the catastrophic failure. Some curves in Figure 2 are not continuous; they shift to the right at some places. The horizontal shift indicates a sudden increase in displacement. It relates to the popping sound during the test. The cause of this shift could be the real deformation of the sample, a slip (or jump) of the gage caused by a stress wave, or a combination of the two. In some tests the clip-on gage was glued on the specimen so gage slip (or jump) could be eliminated; however, the sudden increase in deformation still existed but had a smaller magnitude. Thus, the sudden increase in displacements measured by extensometer might include both components: sample deformation and gage slip.

DAMAGE

Figure 3 shows the radiographs of D and E specimens, which illustrate the damage around the slits. In all cases matrix crackings in 0, 90 and ± 45 degree plies are all noticeable in the damaged area. Major matrix crackings in 0 and ± 45 degree plies are found tangent to the slit boundary. Matrix crackings in 90 degree plies are more evenly distributed without a dominant one. By comparing the damage of 70D specimens at 80 and 90 percent of the failure load, it is clear that at higher load the damaged area is larger and the crack density is higher. Although crack patterns look somewhat similar, they vary among geometries and lay-ups. For example, in specimen 54D3, the 90 degree matrix crackings extend from the end of a slit to the edge of the sample; in specimen 76E6, matrix crackings are clustered along two major cracks in ± 45 degree plies.

Figure 2 Load -displacement curves of D and E specimens

FAILURE

Typical failed D and E samples are illustrated in Figure 4. The 54D samples have fracture planes normal to the loading direction. The side view of these specimens (not shown here) revealed that all plies were broken at the same location except one surface 45 (or -45) degree ply that was debonded from the rest of the laminate. This suggested that 90 degree plies failed by matrix cracking, but 0 and ± 45 degree plies failed by fiber breakage.

Figure 3 Radiographs of D and E specimens

For 76D samples, there is no unique fracture plane. Cracks were all initiated at slit ends, but they propagated in different directions depending on the ply direction. Most of the broken edges of ± 45 degree plies are ± 45 degree from the direction of loading; that is, the fracture is parallel to the fiber direction. Therefore, the failure of ± 45 degree plies is mostly matrix cracking. A large fractured zigzag area can be seen from the side of the specimen. The failure mode of 70D samples falls in between 54D and 76D cases.

Broken samples of 54E and 70E show their failure modes are similar to 54D; there is a common fracture plane with the exception of the surface plies. The failure surface of 76E samples is comparable to 70D; both fiber breakage and matrix cracking are observed in the ± 45 degree plies.

Figure 4 Failed specimens

FINITE ELEMENT MODELING

In the computational study, we used the commercial finite element code ABAQUS [3] and a user defined material damage model to predict the notch strength of the tested laminates. Results generated from the above experiments were used to assess the accuracy of this modeling method.

The damage model implemented into ABAQUS was based on a progressive failure model recently proposed by Shahid and Chang [2]. The model predicted the type of failure, the extent of damage, and the degradation in material properties as the loading progressed and failure occurred. Only three in-plane failure modes were considered: matrix cracking, fiber matrix shear-out, and fiber tensile breakage. Failure and damage were tracked at the element level for each layer. A crack density state variable (number of cracks per inch) measured the extent of damage in the matrix. A cumulative fiber failure area state variable measured the extent of damage in the fibers. More details on the theory of the implemented damage model can be found in reference 2. Shahid and Chang implemented their model in a special purpose code called PDCOMP [2]. In this study, the material damage model was implemented into ABAQUS through provided user interface subroutines UMAT and VUMAT [3]. For computational efficiency, the part for calculating the material degradation due to matrix cracking was not implemented into UMAT and VUMAT. PDCOMP was used to generate these results, which was then used by ABAQUS. Thus, the degradation was not calculated at every material point, and at every increment in the ABAQUS analysis. We believe the error caused by this simplification was small.

A total of fifteen material parameters including moduli, strengths, and statistical parameters for material degradation rules were required for the composite damage model. The same fifteen parameters were used in all analyses, for all laminate configurations. Table 2 shows the values of these parameters for the T800/3900-2 Graphite/Toughened Epoxy composites [4]. These parameters were obtained independent from the above experiments. The standard version of ABAQUS was used to analyze the quasi-static uniaxial tensile load. However, in a few analyses, we encountered numerical convergence problems due to large distortions of elements that had fiber failures. For these analyses, we used the ABAQUS explicit version with mass scaling to by-pass the convergence problem. The uniaxial tensile load of a displacement controlled test was simulated by fixing the bottom edge of the laminates and displacing the top edge upward. Figures 6 and 7 show finite element results for case 76E. These were typical results obtained from the finite element analyses. Figure 6 shows a comparison of the load versus displacement data, the undeformed and the deformed mesh. Figure 7 shows the crack density just before ultimate laminate failure occurred for the first four layers, the 45, 90, -45 and 0 degree plies respectively. These figures can be compared with the 76E6, 90% x-ray radiograph shown in figure 3. Note that in the x-ray photograph, the dye penetrant was only applied in the notch vicinity. Thus any failure far away from the notch can not be seen in the photograph. Both measured and predicted results show very high crack density right around the notch tip. The analysis predicted fiber failure only at the notch tip.

Figure 6 Load-displacement curve, deformed and undeformed meshes

Figure 7 Predicted crack density

Table 2 Material properties and constants used in the calculations

E_{xx}	E_{yy}	G_{xy}	G_{yz}	ν_{xy}	α	X_t	α_{xx}	α_{yy}	T_{cure}	G_{Ic}	G_{IIc}	η	δ	β
MPa	MPa	MPa	MPa			MPa	1/C	1/C	C	kJ/m2	kJ/m2			
152	9.3	6.2	3.7	0.3	8E-15	2.8	4E-07	3E-07	177	0.15	0.28	8	0.055	8

Table 3 summarizes notch strength comparisons between experimental and computational results for all cases. The values of experimentally measured strength are averages of three tests. The average error was 6.8 percent. The standard deviation of the error was 4.7 percent. All predicted strengths were within 15 percent of measured strengths. This result shows that the implemented damage model can predict the notch strength of laminates with different geometry and different lay-up relatively well. Note that no empirical data, such as characteristic length, was used in the analyses to account for the different notch geometries and different lay-ups.

Table 3 Notch strength comparison

Specimen	Measured strength (MPa)	Predicted strength (MPa)	Error (%)
70A	915	979	+ 6.9
70B	396	402	+ 1.5
54B	217	207	- 4.6
76B	291	335	+ 15.2
70C	385	327	- 15.1
70D	386	378	- 2.1
54D	257	280	+ 8.8
76D	317	336	+ 5.9
70E	219	210	- 4.2
54E	145	149	+ 2.8
76E	223	241	+ 8.1

CONCLUSIONS

Experiments to determine the strength and failure mode of symmetric and nonsymmetric cutouts under in-plane tensile loading were performed. A damage accumulation model was implemented into ABAQUS to simulate the experiments. Model predictions of laminate deformation, damage and strength compare favorably with experimental results.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under Contract DE-AC04-94AL85000. The authors wish to thank Ms. Hui Bau at Boeing 777 Empennage Group for providing composite panels and technical discussions. The assistance of Michael Tracy and Yanmin Yan in the experimental work is gratefully acknowledged.

REFERENCES

1. S. Tan, Stress concentrations in laminated composites. Technomic Publishing Co. (1994).
2. I. Shahid, Progressive failure analysis of laminated composites subjected to in-plane tensile and shear loading. Ph.D. dissertation, Stanford (1993).
3. ABAQUS is a commercial general purpose finite element code, Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, Rhode Island, USA. (1994).
4. F.K. Chang, private communication, Stanford (1994).

APPENDIX F—RTM PROCESSING CAPABILITIES

RTM equipment available in Sandia/California IMTL facility.

Resin materials selected and procured.

ASHBY-CROSS 2500 PC-3 RTM MACHINE
AS INSTALLED IN IMTL FACILITY AT SANDIA/CA

RTM EQUIPMENT

For advanced composite manufacturing

FEATURES:

METERING ASSEMBLY: Two positive displacement gear pumps equipped with synchronized electric motor drives, digital RPM readout for each pump, RPM set point counters for ratio, potentiometer for ramp capability, and individual heaters for each pump. Provides Non-Pulse Flow.

RESERVOIRS: Individually sized for the application, each tank is made of stainless steel with vacuum holding capability. Each has an air motor driven agitator with slinger plate for thin film deairing, proportional heating, material shut-off valve and material temperature sensor.

HEATED CART: Portable, containing the entire metering assembly, reservoirs, and pumps.

DELIVERY HOSE: Individually heated and controlled, capable of ramping material temperatures to mold temperature.

VACUUM PUMP AND GAUGE: Includes oil mist eliminator, filter/trap on intake side of pump, vacuum hoses to tanks.

MIXER HEAD: Static or Dynamic Mixers available. Static Mixer equipped with catalyst injector valve to prevent resin and catalyst mixing prior to the static mixer. Fluid gauges mounted on the inlet of the mixer manifold. Control is hand held electric start/stop button.

SOLVENT/AIR PURGE: 3 gallon ASME stainless steel pressure tank with regulator, gauge, on/off air valve, and selector valve for solvent/air purge cycle.

FLOW METERS: Mounted on outlet side of metering pumps, the microprocessor is capable of real time ratio monitoring with alarm and other programmable features.

CONTROL CONSOLE: Proportional heat controllers for up to nine heat zones, emergency shut off, ratio readout, on/off controls for all heat zones, auto shot timer, flush control, vacuum and pump.

ADVANTAGES

Provides accurate repeatable Non-Pulse flow of components, allows variable flow rates and variable ratio by motor speed control.

Temperature ramping capability to ensure proper heating of materials.

Ratio monitor provides immediate data on ratio and flow along with data storage.

Vacuum holding reservoirs provide Air-Free material delivery to the mold, as well as the ability to meter under slight vacuum.

Static or dynamic mixing provides a complete range of mixing capability for all two component materials.

SPECIFICATIONS

- Operates under vacuum
- Volumetric ratio range: 1:1 through 40:1
- Ratio accuracy: $\pm 2\%$
- Viscosity range: to 20,000 CPS
- Dispense rate range: 25 cc/min to 2000 cc/min
- Injection pressure: Variable from 0 - 200 psi
- Injection volume: Up to capacity of reservoirs
- Temperature capability: to 350° F with ramp capability of 5 deg./min.

Ashby-Cross Company, Inc.

418 Boston Street, Topsfield, MA 01983 □ (508) 887-2887 □ FAX (508) 887-3829

SECTION I

ARTICLE 1. - STATEMENT OF WORK

Provide the following deliverables to Sandia National Laboratories, CA:

ITEM	QTY	UNIT	DESCRIPTION	UNIT PRICE	EXTENSION
1.	1	ea	Resin Transfer Molding - Meter, Mix and Dispense machine per RFQ.	\$_____	\$_____

BACKGROUND

The machine is intended for laboratory and prototyping use and requires versatility in terms of resin selection, processing conditions, mold/part size, ease of use, and ease of cleaning up.

GENERAL SPECIFICATIONS

The machine should have the following component capabilities and/or performance characteristics.

1. Cylinder metering system using stepping motor(s) drive.
2. Variable ratio from 1:1 to 20:1 is required. Provide an option for additional cylinders to increase ratios from 20:1 to 150:1.
3. A ratio accuracy of $\pm 1\%$ or better.
4. An easy method of sampling the ratio between the A and B sides at ambient temperature.
5. Viscosity range from 100 cps to 50,000 cps at temperature.
6. Independent heating of Side A and Side B from room temperature to 225°F. If not possible, provide an option/alternative method.
7. Material outlet hoses for A and B sides 5' in length or greater Teflon lined, stainless steel braided and completely heatable up to 300°F or more.
8. Versatility to process one (1) or two (2) component materials that are liquid at ambient temperature, and are non-flammable and non-explosive.
9. All O rings should be made from any of these materials; Viton, Teflon, or Kalrez.

SECTION I

10. Reservoirs should have a sensing device or view port to monitor the material level.
11. Both reservoir tanks should hold a minimum of two (2) gallons and a maximum of three (3) gallons of material and be stainless steel, have self contained agitators (for mixing resin and fillers including hollow microspheres) and be capable of vacuum degassing to 5 torr.
12. The machine should be capable of injection pressures from 0 psi up to 500 psi and remain accurate within ± 5 psi. If not possible, provide an option/alternative method.
13. The machine should have a flow rate range of 50 cc per minute at lower end and up to 700 cc per minute at 1:1 ratio.
14. A method to measure and control (1) temperatures in all zones, an (2) flow rate and (3) measure pressure at the tool. There should be connections to down load readings of temperatures, flow rate and pressure. All to be incorporated in the main control panel. If not possible, provide an option/ alternative method.
15. Provide an easy method to purge the entire system, including a way to isolate mixing head for air or solvent purging.
16. The entire unit should be portable, with a power cable of 20 feet or more.
17. The machine and associated components should be painted with resin/solvent resistant paint. The preferred color is blue with the exact shade to be determined.
18. Control panel should be equipped with a panic stop palm button.
19. Material outlet hoses should be secured in a manner to prevent or minimize any whipping in case of puncture.
20. Contractor should provide complete and comprehensive instruction on the use of equipment for two (2) or more Sandia employees at a location of the Contractor's choice.
21. Start-up training shall be performed at Sandia National Laboratories, Livermore, California.
22. A one (1) year (or longer) full coverage warranty shall be provided from the date of delivery and/or acceptance.
23. Unlimited phone consultation with service personnel shall be provided indefinitely.
24. A 48 hour response by service personnel is required.

SECTION I

25. It is desirable for the machine and any applicable components to fit within an envelope of 72 inches long by 48 inches wide by 72 inches tall.
26. It is desirable for the machine to utilize 208V, single or 3 phase power. Contractor to specify power and plug type.
27. Additional modifications or options that serve the same purpose as the previously mentioned, and as determined applicable by the vendor, shall be completely explained and described.

ARTICLE 2. - DELIVERY

Delivery required at Sandia on or before December 31, 1993.

ARTICLE 3. - PRICE

Total Price: \$_____

ARTICLE 4. - ACCEPTANCE

Acceptance will occur, Warranty period shall begin, and payment will be made subsequent to the successful installation at the Sandia National Laboratories, Livermore, facility, of the items described in Article 1 and demonstration that the items can meet the Mandatory Specifications set forth in Article 1 and any Desirable Features claimed by the Contractor.

ARTICLE 5. - MANUFACTURING AND TESTING STANDARDS - 613-MT (8-92)

- A. Unless excluded or modified elsewhere in this contract/order, Contractor warrants that all equipment, components, tools and products of any nature whatsoever, furnished under this contract, shall be manufactured and/or tested in accordance with standards normally associated with such items when they are sold to users in the United States. Examples of such manufacturing and/or testing standards include, but are not limited to:
 - o Underwriter's Laboratory (UL) Listing
 - o National Fire Protection Association Approval
 - o Occupational Safety and Health Act (OSHA) Approval
 - o American Society for Testing Material (ASTM) Certification
 - o Nationally Recognized Testing Laboratory (NRTL) Approvals
- B. All items furnished under this contract shall be clearly marked and/or labelled, as appropriate; and, if applicable, all items shall be accompanied by installation and/or operating instruction normally associated with such items.

*Specialists in all aspects of
Resin Transfer Molding Technology*

HYPAJECTTM

Mark II Resin Injection System

HYPAJECTTM Mark II is a new concept in resin transfer molding equipment. Developed out of a greater need to simplify the handling of thermoset resins and their multitude of additives, HYPAJECTTM Mark II provides an economic and versatile equipment alternative for producers of reinforced and unreinforced moldings.

HYPAJECTTM Mark II is designed to inject/dispense a variety of thermosetting resins, under pressure, to manufacture reinforced and unreinforced moldings. These materials include; unsaturated polyester, vinylester, epoxy, methyl methacrylate, etc.

**HYPAJECTTM Mark II
is available in the following capacities:**

Model 3	1 gallon
Model 6	2 gallon
Model 6 Mark II	2 gallon

RTM SYSTEMS, INC. offers a range of resin transfer molding products including both manual and automatic HYPALOCKTM clamp/jack systems for RTM and other closed molds. A comprehensive supply of RTM technology is also available from RTM SYSTEMS, including RTM Tooling Training Seminars.

...another RTM solution from RTM SYSTEMS, INC.

HYPAJECT for Versatility...

- ... is capable of pressure injecting any resin, color, filler, accelerator or catalyst combination into closed molds.
- ... will inject all thermosetting resins including: polyester, vinylester, methacrylate, phenolic, epoxy, etc.
- ... can take in and inject as little as a cupful of mixture at a time, no machine priming required.

HYPAJECT for Accuracy...

- ... homogeneous mixture cure profile eliminates distortions due to inaccurate catalysation.
- ... quality and type of resin mix is determined and assured before injection.
- ... control and indication of actual injection pressure.
- ... zero to maximum injection flow throttle control.
- ... total pneumatic operation and control with safe, audible mixture indicator.

HYPAJECT for Economy...

- ... smaller models require only a 1/2 HP "plug-in" portable air compressor for full operation.
- ... extremely low material wastage and energy consumption.
- ... will use the same cleaning solvent over and over again.
- ... no machine priming means major savings between material mixture and color changes.
- ... is compact and lightweight (Model 3 weighs 30 lbs.), for simple installation, operation and ease of maintenance.
- ... only one moving part means very low maintenance costs.

HYPAJECT™ 3

Operating Specifications:

Output:	Max. .8 gal / 10 seconds
Air Supply:	90 psi at 1.5 cfm

Shipping Specifications:

Weight:	30 lbs.
Dimensions:	35" X 12" X 10"

For More Information:

Contact RTM SYSTEMS, INC. for details regarding the RTM Tooling Seminars and other resin transfer molding products and services.

HYPAJECT and HYPALOCK are registered trademarks of Plastech T.T.

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Phone (317) 875-7174 **Fax (317) 875-5456**

Sandia National Laboratories
Albuquerque, NM 87185

DATE: December 14, 1994

TO: Distribution

FROM: G. M. Jamison, 1812, MS 0367

SUBJECT: Materials for IMPReS

After surveying the commercially available RTM-processable matrix resins and curing agents, it appears that there are really only a few epoxies suitable for fabricating structural parts by RTM under the IMPReS project. Considerations in selecting these resin systems include Sandia's familiarity with epoxy thermosets, the potential benefit to DP as we establish expertise with RTM, and the potential extension of cure-stress modeling of Shell Epon 828/DEA to other epoxy materials. Also, limited quantities of these materials are on hand, so that we may begin characterizing and collecting data on curing immediately; some of you may notice that they are components of the 456 and 459 formulations finding a number of receptive DP customers.

Those familiar with the commercially available resins/cure agents and their general characteristics were able to identify two classes of simple diglycidyl ethers and agree that the following materials are worthy of preliminary investigations:

1. Shell EPON 826, a low-viscosity alternative to the well-known 828 bis-A formulation.
2. Shell EPON 862, a low-viscosity bis-F material touted to have better resistance to corrosives and chemicals, and comparable thermal and mechanical properties to the bis-A resins.
3. Dow Tactix 123 and 138, both bis-A epoxy resins (very high purity).

Amine curing agents were selected based on supplier viscosity and T_g data and the guiding consideration that MDA and other aromatic polyamines are an invitation to complications from ES&H; the appropriate aliphatic amines which were chosen include:

1. Air Products Amicure PACM and Ancamine 2049 (both cycloaliphatic diamines).
2. Air Products Ancamine 2167 (a polycycloaliphatic amine).

3. Huntsman (formerly Texaco) Jeffamine D-230 (a polyether-bridged diamine).

Specific properties of these materials are available from the suppliers and/or should be easy for us to verify/determine prior to use.

In the event that these resin/curing agent formulations do not yield cured parts with any appreciable thermal or mechanical properties, a pair of alternative high-performance tri- and tetraglycidyl ethers have been identified to impart better characteristics:

1. Ciba Geigy Araldite MY 721 (tetrafunctional).
2. Ciba Geigy Araldite MY 0510 (trifunctional).

Bis-A; Epon 826, Tactix 123,138

Bis-F; Epon 862

Araldite MY 721

Araldite MY 0510

SHELL RESINS

EPON[®] RESIN 862/⁽¹⁾ EPI-CURE[®] W Curing Agent⁽²⁾

⁽¹⁾Formerly EPON[®] Resin DPL-862
⁽²⁾Formerly EPON Curing Agent[®] W
⁽³⁾Formerly EPON Curing Agent[®] Accelerator 537

General description

The EPON® Resin 862/EPI-CURE® W Curing Agent system consists of an epoxy bisphenol F resin and aromatic amine for fabricating composite parts using resin transfer molding (RTM) and filament winding. EPI-CURE W Curing Agent does not contain methylene dianiline (MDA). Low tendency to crystallize, low viscosity and very long working life at room temperature make this system versatile and easy to process. EPI-CURE Curing Agent Accelerator 537⁽³⁾ may be utilized to decrease the gel time of the system with little or no effect on mechanical properties.

Advantages

- Resistance to crystallization
- Low room temperature viscosity (about 2200 cP)
- Long working life (>20 hrs.)
- Low moisture absorption (2-2.5 wt%)
- Good epoxy performance characteristics
- Non-MDA aromatic amine
- High elongation

Applications

- Advanced composite structures
- Resin transfer molding (RTM)
- Filament winding

Chemical description

- EPON Resin 862 – Epoxy bisphenol F (BPF) resin
- EPI-CURE W Curing Agent – Non-MDA, aromatic amine curing agent
- EPI-CURE Curing Agent Accelerator 537

Typical properties

Components

EPON® Resin 862

Epoxide equivalent weight, g/g-equiv.	166-177
Viscosity, Poise at 77 °F	30-45
Weight per gallon, lbs. at 68 °F	97-99
Flash point, Setaflash	>300°F

EPI-CURE® W Curing Agent

Amine nitrogen, g/g-equiv.	43-46
Viscosity, Poise at 68 °F	3.0-3.5
Weight per gallon, lbs. at 68 °F	8.4-8.6
Flash point, TCC	275°F

EPI-CURE Curing Agent Accelerator 537

Viscosity, Poise at 75 °F	6.0-25
Weight per gallon, lbs. at 68 °F	10.7-10.9
Flash point, PMCC, °F	>400
Water content, wt%	<2

Mixed System

Mix ratio, parts by weight	100/26.4/0	100/26.4/1
Viscosity, Poise at 77 °F	21-23	21-23
Pot life, hrs. at 77 °F	21.5	7.9
Gel time, mins. at 350 °F	4.1	15

Neat resin system properties

Unaccelerated

The cured, unaccelerated, neat resin properties of the EPON Resin 862/EPI-CURE W Curing Agent resin system as a function of cure time at 250 °F and 350 °F are provided in Table 1. The isothermal and dynamic viscosity curves of this system are shown in Figures 1 and 2.

Table 1/Properties of the EPON® Resin 862/EPI-CURE® W Curing Agent resin system (100/26.4) as a function of cure time

Cure schedule, hrs. at 350 °F	0.5	1.5	2.5
Density, g/cc	—	1.2003	
Specific heat, cal/g °C or BTU/lb °F			
77 °F	—	—	0.31
140 °F	—	—	0.34
230 °F	—	—	0.39
Glass transition temperature			
°F, Rheometrics	266	302	322
°F, DSC	273	289	313
Fracture toughness, Kq			
Compact tension, psi-in ^{1/2}	528	657	820
Flexure, RT/Dry			
Strength, ksi	No failure	12.5	18.6
Modulus, ksi	458	433	424
Elongation, %	No failure	7.9	8.3
Flexure, Hot/Wet			
Strength, ksi	8.1	9.4	8.9
Modulus, ksi	314	310	305
Elongation, %	4.6	5.5	6.4
Water absorption, wt%	2.2	2.1	2.1
Tensile, RT/Dry			
Strength, ksi	—	—	11.4
Modulus, ksi	—	—	394
Elongation, %	—	—	7.1
Dielectric properties			
Dielectric strength, V/mil 100 KHz	—	—	563
Dielectric constant	—	—	3.98
Dissipation	—	—	0.0293
Volume resistivity, ohm-cm	—	—	1.54E8
Cure schedule, hrs. at 250 °F	4	8	
Glass transition temperature			
°F, Rheometrics	235	273	
°F, DSC	—	—	
Fracture toughness, Kq			
Compact tension, psi-in ^{1/2}	541	583	
Flexure, RT/Dry			
Strength, ksi	18.4	18.0	
Modulus, ksi	496	455	
Elongation, %	7.5	8.5	
Flexure, Hot/Wet			
Strength, ksi	9.5	9.0	
Modulus, ksi	300	295	
Elongation, %	6.6	6.2	
Water absorption, wt%	2.2	2.2	
Tensile, RT/Dry			
Strength, ksi	11.7	12.0	
Modulus, ksi	471	431	
Elongation, %	8.2	8.5	

Isothermal and dynamic viscosity curves for the EPON Resin 862/EPI-CURE W Curing Agent (26.4 phr) resin system are shown in Figures 1-4.

Figure 1/Isothermal viscosity sweeps for EPON® Resin 862/EPI-CURE® W Curing Agent using a Rheometrics Parallel Plate Viscometer

Figure 2/Viscosity cure sweep for EPON® Resin 862/EPI-CURE® W Curing Agent at 5 °C/min using a Rheometrics Parallel Plate Viscometer

Neat resin system properties

Accelerated

The cured, accelerated, neat resin properties of the EPON Resin 862/EPI-CURE W Curing Agent resin system as a function of cure time at 250 °F and 350 °F and accelerator concentration are provided

in Tables 2 and 3. The isothermal and dynamic viscosity curves of this system at 1.0 phr of EPI-CURE Curing Agent Accelerator 537 are shown in Figures 3 and 4.

Table 2/Properties of the EPON® Resin 862/EPI-CURE® W Curing Agent/EPI-CURE® Curing Agent Accelerator 537 resin system (100/26.4/0.5) as a function of cure time

Cure schedule, hrs. at 350 °F	0.5	1.5	2.5
Density, g/cc	—	—	1.1947
Specific heat, cal/g °C or BTU/lb °F			
77 °F	—	—	0.32
140 °F	—	—	0.35
230 °F	—	—	0.40
Glass transition temperature			
°F, Rheometrics	266	284	302
°F, DSC	230	279	288
Fracture toughness, Kq			
Compact tension, psi-in ^{1/2}	578	698	727
Flexure, RT/Dry			
Strength, ksi	17.1	17.2	17.5
Modulus, ksi	468	434	437
Elongation, %	9.9	8.6	8.5
Flexure, Hot/Wet			
Strength, ksi	4.6	7.6	5.4
Modulus, ksi	282	300	313
Elongation, %	6.9	6.9	6.8
Water absorption, wt%	2.5	2.1	2.1
Tensile, RT/Dry			
Strength, ksi	—	—	10.0
Modulus, ksi	—	—	408
Elongation, %	—	—	4.7
Dielectric properties			
Dielectric strength, V/mil 100 KHz	—	—	578
Dielectric constant	—	—	3.96
Dissipation	—	—	0.0303
Volume resistivity, ohm-cm	—	—	1.50E8
Cure schedule, hrs. at 250 °F	4	8	
Glass transition temperature			
°F, Rheometrics	253	273	
°F, DSC	—	—	
Fracture toughness, Kq			
Compact tension, psi-in ^{1/2}	650	569	
Flexure, RT/Dry			
Strength, ksi	18.2	18.0	
Modulus, ksi	4780	463	
Elongation, %	8.1	8.3	
Flexure, Hot/Wet			
Strength, ksi	9.0	8.9	
Modulus, ksi	292	288	
Elongation, %	5.1	5.2	
Water absorption, wt%	2.2	2.3	
Tensile, RT/Dry			
Strength, ksi	11.7	12.0	
Modulus, ksi	466	457	
Elongation, %	10.3	8.7	

Table 3/Properties of the EPON® Resin 862/EPI-CURE® W Curing Agent/EPI-CURE® Curing Agent Accelerator 537 resin system (100/26.4/1.0) as a function of cure time

Cure schedule, hrs. at 350 °F	0.5	1.5	2.5
Density, g/cc	—	—	1.2010
Specific heat, cal/g °C or BTU/lb °F			
77 °F	—	—	0.30
140 °F	—	—	0.33
230 °F	—	—	0.41
Glass transition temperature			
°F, Rheometrics	248	302	302
°F, DSC	219	293	300
Fracture toughness, Kq			
Compact tension, psi-in ^{1/2}	772	741	715
Flexure, RT/Dry			
Strength, ksi	20.0	18.1	18.9
Modulus, ksi	506	450	453
Elongation, %	7.8	6.7	8.4
Flexure, Hot/Wet			
Strength, ksi	9.3	8.6	9.1
Modulus, ksi	316	292	298
Elongation, %	4.9	5.5	5.2
Water absorption, wt%	2.3	2.1	2.0
Tensile, RT/Dry			
Strength, ksi	—	—	11.5
Modulus, ksi	—	—	401
Elongation, %	—	—	6.8
Dielectric properties			
Dielectric strength, V/mil 100 KHz	—	—	562
Dielectric constant	—	—	3.90
Dissipation	—	—	0.0289
Volume resistivity, ohm-cm	—	—	1.60E8
Cure schedule, hrs. at 250 °F	4	8	
Glass transition temperature			
°F, Rheometrics	235	291	
°F, DSC	—	—	
Fracture toughness, Kq			
Compact tension, psi-in ^{1/2}	620	543	
Flexure, RT/Dry			
Strength, ksi	19.0	17.8	
Modulus, ksi	516	455	
Elongation, %	7.3	8.5	
Flexure, Hot/Wet			
Strength, ksi	9.2	8.7	
Modulus, ksi	295	283	
Elongation, %	5.2	6.2	
Water absorption, wt%	2.3	2.2	
Tensile, RT/Dry			
Strength, ksi	11.8	12.1	
Modulus, ksi	484	425	
Elongation, %	5.9	8.2	

Figure 3/Isothermal viscosity sweeps for EPON® Resin 862/EPI-CURE® W Curing Agent/
EPI-CURE® Curing Agent Accelerator 537 using a Rheometrics Parallel Plate Viscometer

Figure 4/Isothermal viscosity sweeps for EPON® Resin 862/EPI-CURE® W Curing Agent/EPI-CURE®
Curing Agent Accelerator 537 at 5 °C/min using a Rheometrics Parallel Plate Viscometer

Composite fabrication

Resin transfer molding (RTM)

The low viscosity feature of EPON Resin 862/EPI-CURE W Curing Agent permits low injection pressures, less fiber washout, high filler/fiber loadings, and lower mold costs for RTM fabrication processes. An ambient temperature, one-pot, RTM process may be employed in which the mixed resin/curing agent increases from 2200 cP initially to 5000 cP after about 36 hrs. Processing data for this system is provided in Table 4. Alternatively, a two-pot resin and curing agent system can be used in which either the resin or both pots may be heated, generally less than 140 °F unless otherwise required. A typical process includes injecting into a heated mold at 250 °F (system viscosity is on the order of 10 cP at 250 °F) and curing in the mold for

between 0.5-1.5 hrs. at 350 °F followed by a 350 °F posture for another hour. Molding and post-cure temperature and times can be modified for optimum production. Isothermal viscosity traces (see Figure 1) can be used to select the process conditions based on fill viscosity and cure time criteria. EPI-CURE Curing Agent Accelerator 537 can be used to help modify the cure schedule according to processing (Figure 3) and property requirements. Air release agents, such as BYK® A-501* or equivalent, may be added if air entrainment problems are encountered. Carbon fiber reinforced composite test data are presented in Table 5.

*A product of BYK Chemie

Table 4/Processing data for the EPON® 862/EPI-CURE® W CURING AGENT resin system (26.4 phr) as a function of EPI-CURE®Curing Agent Accelerator 537 level

EPI-CURE Curing Agent Accelerator 537 level, phr	0.0	0.5	1.0
Pot life, hrs. at 77 °F	21.5	8.5	7.9
Gel time, min.			
250 °F	94.6	45.4	30.5
300 °F	30.3	14.7	12.0
350 °F	15.0	7.4	4.1

Table 5/Mechanical properties for the EPON® Resin 862/EPI-CURE® W Curing Agent resin system (26.4 phr) fabricated using resin transfer molding (RTM) with unidirectional and 8 harness satin woven graphite fabrics

	Unidirectional	8HS
0° Tensile, RT/Dry		
Strength, KSI	314	—
Modulus, MSI	18.4	—
Elongation, %	—	—
0° Compressive, RT/Dry		
Strength, ksi	210	—
Modulus, msi	18.7	—
Elongation, %	1.3	—
0° Compressive, Hot/Dry		
Strength, ksi	168	—
Elongation, T	1.0	—
0° Compressive, RT/Wet		
Strength, ksi	212	—
Elongation, %	2.0	—
0° Flexure, RT/Dry		
Strength, ksi	—	122
Modulus, msi	—	10.0
Elongation, %	—	1.5
0° Short beam shear strength, ksi	—	8.2
Tensile test method	ASTM D-3039	
Compressive test method	Modified ASTM D-695	
Flexure test method	ASTM D-790	
Short beam shear		
Strength test method	ASTM D-2344	
RT/Dry	Tested at ambient temperature/humidity (75 °F/50% R.H.)	
RT/Wet	Conditioned for 2 weeks in 200 °F (93 °C) water. Tested at ambient temperature/humidity (75 °F/50% R.H.)	
Hot/Dry	Tested at 200 °F (93 °C). No water conditioning.	
8HS	8 Harness satin woven fabric with 3K Celion G30-500 fibers.	
Uni	Unidirectional woven fabric with 3K Toray T400 fibers with fiberglass cross fibers.	

Composite fabrication

Filament winding

The low viscosity and long room temperature pot life of EPON Resin 862/EPI-CURE W Curing Agent make it suitable for use in wet filament winding applications. The material may be used at room temperature or heated to reduce viscosity and facilitate fiber wetout. The initial mixed system viscosity of 2200 cP may be reduced to approximately 1000 cP by heating the system to about 40 °C (100 °F). The pot life at this temperature is in excess of 8 hours, sufficient for winding large or complex parts. EPON Resin 862/EPI-CURE W Curing Agent is suitable for use with glass, carbon, and Kevlar®* reinforcements. If air entrainment during mixing or fiber impregnation proves to be a problem, air release agents such as BYKA-501 or equivalent may be added. Cure may be conducted through internal heat sources in the mandrel or externally with ovens or both. Additional resin/reinforcement compaction may be accomplished during cure using traditional vacuum and pressure techniques. Frequently, a staged cure is most desirable in order to minimize resin runout and void formation in the composite. If shrinkwrap, vacuum bagging, or other external containment are not utilized, it is recommended that the part be rotated during cure to ensure uniform resin distribution through the part. A suggested cure cycle would include 1 hour at 121 °C (250 °F) plus 2.5 hours at 177 °C (350 °F).

Packaging and storage

EPON Resin 862 is currently available in 1, 5, and 55-gallon containers and is a stable liquid at room temperature. EPON Resin 862 is not a hazardous material according to Department of Transportation regulations.

EPI-CURE W Curing Agent is currently available in 1 and 5-gallon containers and is a stable liquid when stored unopened at room temperature. EPI-CURE W Curing Agent is not a hazardous material according to Department of Transportation regulations. Although stable at room temperature in an unopened container, this material will become

darker in color with exposure to the atmosphere. This may result in color changes in the final cured component. Evidence indicates this phenomenon does not affect the material's performance. Please contact a Shell technical representative if further information is needed.

Handling precautions

The recommendations for material selections made in this technical bulletin are based on Shell's experience and research and are believed to be sound technical approaches to the applications or end uses for which they are presented. However, these recommendations are directed toward technical performance and should not be taken as recommendations pertaining to health, safety, or the environment.

EPON Resin 862, EPI-CURE W Curing Agent, EPI-CURE Curing Agent Accelerator 537 and the auxiliary materials normally combined with this system are capable of producing adverse health effects ranging from minor skin irritation to serious systemic effects. Exposure to these materials should be minimized and avoided if feasible through the observance of proper precautions, use of proper personal protective clothing and equipment, and adherence to proper handling procedures. Each of these preventive measures depends upon responsible action by adequately informed persons. **None of these materials should be transported, stored, or used until handling precautions and recommendations are understood as stated in the Material Safety Data Sheets (MSDSs) #800674, #800520 and #800391, respectively by all persons who will work with them.** Questions and requests for information on Shell products should be directed to your Shell Chemical Company Sales Representative or to the nearest Shell Chemical Sales office. Information on non-Shell products should be obtained from the respective manufacturer or vendor.

*A product of E.I. Du Pont de Nemours & Co., Inc.

Warranty

All products purchased from or supplied by Shell are subject to terms and conditions set out in the contract, order acknowledgement and/or bill of lading. Shell warrants only that its product will meet those specifications designated as such herein or in other publications. All other information supplied by Shell is considered accurate but is furnished upon the express condition the customer shall make its own assessment to determine the product's suitability for a particular purpose. **Shell makes no other warranty, either express or implied, including those regarding such other information, the data upon which the same is based, or the results to be obtained from the use thereof; that any product shall be merchantable or fit for any particular purpose; or that the use of such other information or product will not infringe any patent.**

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CYCLOALIPHATIC AMINE/EPOXY RESIN FORMULATIONS FOR RTM

Epoxy resin formulations are often used for resin transfer molding (RTM) to attain excellent physical and mechanical properties. Cycloaliphatic amines are ideal curing agents for epoxy RTM applications. Low- to moderate-viscosity epoxy resins, such as D.E.R. 383, Tactix 123 and Epon 826, when combined with Amicure® PACM and Ancamine® 2167 curing agents, exhibit the processing behaviors required for resin transfer molding and the excellent mechanical performance required for industrial composite matrices. A wide range of thermal and mechanical performance requirements can be met by varying cycloaliphatic amine curing agent, epoxy resin and cure schedule.

CYCLOALIPHATIC AMINE-CURED FORMULATIONS EXHIBIT PROCESSING BEHAVIORS IDEAL FOR RTM

Amicure PACM and Ancamine 2167 curing agents are low-viscosity cycloaliphatic amines. As shown in Figure 1, formulations of these cycloaliphatic amine curing agents with liquid DGEBA epoxy resin exhibit 25 °C pot life for two to five hours, depending on the epoxy resin selected.

Formulations of cycloaliphatic amine curing agents and low-viscosity DGEBA epoxy resins such as Tactix 123 exhibit long pot life while maintaining the rapid gelation and development of cure required for cost-effective RTM part fabrication.

FIGURE 1: 25 °C FORMULATION VISCOSITY PROFILES FOR CYCLOALIPHATIC AMINE/EPOXY RESIN FORMULATIONS

AMICURE PACM FORMULATION VISCOSITY PROFILES

ANCAMINE 2167 FORMULATION VISCOSITY PROFILES

In Figure 2, the formulations have been subjected to thermal profiles representative of typical RTM injection profiles: 1) 15 minutes at 70 °C, followed by heating at 10 °C/minute to 100 °C, and 2) 15 minutes at 70 °C followed by heating at 10 °C/minute to 150 °C. In each example, the cycloaliphatic amine-cured resin systems exhibit a low-viscosity plateau during the first 20 minutes of the thermal profile. This low viscosity allows for constant flow throughout the mold. Once the mold temperature is increased to the cure temperature, the cycloaliphatic amine-cured formulations gel and continue to develop cure rapidly. The excellent low-temperature reactivity of Amicure PACM and Ancamine 2167 cycloaliphatic amine curing agents contributes to the rapid development of cure in the mold. As shown in Figure 3, the glass transition temperature of the cycloaliphatic amine-cured DGEBA epoxy resin increases rapidly during cure at 150 °C. The rapid development of T_g for the cycloaliphatic amine-cured formulations will lead to rapid development of "green strength" and may lead to reduced cycle times.

MECHANICAL PERFORMANCE OF CYCLOALIPHATIC AMINE-CURED EPOXY RESINS

Cycloaliphatic amine-cured formulations exhibit high strength and modulus as well as ductility and toughness. The thermal and mechanical performance of cycloaliphatic amine/epoxy resin castings have been characterized after three cure schedules:

1. 15 minutes at 70 °C, 10 °C/minute heating to 100 °C, and 30 minutes at 100 °C

FIGURE 2: COMPLEX VISCOSITY PROFILES FOR CYCLOALIPHATIC AMINE/EPOXY RESIN FORMULATIONS SUBJECT TO STANDARD RTM THERMAL PROFILES

**AMICURE PACM/EPON 826
15 MINUTES AT 70 °C,
10 °C/MINUTE TO 100 °C**

**AMICURE PACM/TACTIX 123
15 MINUTES AT 70 °C,
10 °C/MINUTE TO 100 °C**

**AMICURE PACM/TACTIX 123
15 MINUTES AT 70 °C,
10 °C/MINUTE TO 150 °C**

**AMICURE 2167/EPON 826
15 MINUTES AT 70 °C,
10 °C/MINUTE TO 100 °C**

**AMICURE 2167/TACTIX 123
15 MINUTES AT 70 °C,
10 °C/MINUTE TO 100 °C**

**ANCAMINE 2167/TACTIX 123
15 MINUTES AT 70 °C,
10 °C/MINUTE TO 150 °C**

- II. 15 minutes at 70 °C,
10 °C/minute heating to 100 °C,
and 60 minutes at 100 °C
- III. 15 minutes at 70 °C,
10 °C/minute heating to 150 °C,
and 120 minutes at 150 °C

Curing agent selection, epoxy resin selection, and cure temperature will each significantly impact the thermal and mechanical performance of the cured epoxy matrix. Amicure PACM-cured systems will exhibit higher ductility than Ancamine 2167-cured systems. Ancamine 2167-cured systems will exhibit high modulus while maintaining tensile strength comparable to Amicure PACM-cured systems. The range of DGEBA epoxy resins considered here vary not only in processing behavior, but in mechanical behavior as well. Lower temperature cure may result in excellent ductility, reduced glass transition temperature, and reduced chemical resistance. Higher temperature cures will improve thermal performance and chemical resistance while maintaining good strength, stiffness and ductility.

As shown in Table 1, curing agent choice can significantly impact the mechanical and thermal performance of the epoxy matrix. Amicure PACM- and Ancamine 2167-cured DGEBA epoxy resin exhibit distinctly different mechanical behaviors, regardless of cure schedule. Amicure PACM-cured formulations exhibit increased ductility compared to Ancamine 2167-cured formulations, and Ancamine 2167-cured formulations are characterized by increased modulus compared to Amicure PACM-cured formulations. At cure temperatures ~150 °C and higher, Ancamine 2167-cured formulations exhibit increased glass transition temperatures compared to Amicure PACM-cured formulations.

FIGURE 3: DEVELOPMENT OF GLASS TRANSITION TEMPERATURE: CURED 15 MINUTES AT 70 °C, HEATED 10 °C/MINUTE TO 150 °C AND CURED AT 150 °C

Cycloaliphatic Amine-Cured Formulations Exhibit Rapid Development of Cure

TABLE 1: IMPACT OF CURING AGENT CHOICE ON THERMAL AND MECHANICAL PERFORMANCE

Formulation	Cure Schedule	Tensile Modulus, ksi	Tensile Strength, ksi	% Elong. @ Failure	T _g , °C
Amicure PACM/Tactix 123	15 min at 70 °C, 60 min at 100 °C	385	12.3	6.7	125
Ancamine 2167/Tactix 123	15 min at 70 °C, 60 min at 100 °C	423	12.6	6.2	125
Amicure PACM/Tactix 123	15 min at 70 °C, 120 min at 150 °C	365	11.6	7.2	169
Ancamine 2167/Tactix 123	15 min at 70 °C, 120 min at 150 °C	375	11.8	6.6	167

When selecting epoxy formulations for resin transfer molding, resin selection can significantly impact the matrix performance as well as the processing behavior. Tactix 123, D.E.R. 383, and Epon 826 are low to moderate-viscosity DGEBA epoxy resins. As the data in Table 2

indicate, cured Tactix 123 exhibits the advantageous combination of high strength and ductility. D.E.R. 383 formulations exhibit high strength, ductility and glass transition temperatures while Epon 826 formulations exhibit high moduli.

Due to the low-temperature reactivity exhibited by cycloaliphatic amines, cure temperatures can range from 100 to 175 °C. The cure schedule chosen will govern the mechanical and thermal performance of the epoxy matrix, as shown in Table 3. At 100 °C, the T_g of the cured matrix will not exceed 120 to 130 °C. The mechanical performance of the castings characterized did not change with continued cure at 100 °C after cure for 15 minutes at 70 °C followed by cure for 30 minutes at 100 °C. On the other hand, cure at 150 °C dramatically increases the glass transition temperature and reduces the ductility of the cured matrices.

CONCLUSIONS

The data presented here will enable formulators and composite fabricators to select the cycloaliphatic amine curing agent/epoxy resin formulation that will exhibit requisite viscosity profile during injection and cure and that will cure to form a matrix that exhibits the necessary thermal and mechanical performance. Formulations of epoxy with Amicure PACM and Ancamine 2167 curing agents exhibit a unique and ideal combination of low viscosity, rapid development of cure, and excellent thermal and mechanical performance, making these cycloaliphatic amines ideal curing agents for resin transfer molding.

The information contained herein is offered without charge for use by technically qualified personnel at their discretion and risk. All statements, technical information and recommendations contained herein are based on tests and data which we believe to be reliable, but the accuracy or completeness thereof is not guaranteed and no warranty of any kind is made with respect thereto.

TABLE 2: IMPACT OF EPOXY RESIN CHOICE ON THERMAL AND MECHANICAL PERFORMANCE

Formulation	Cure Schedule	Tensile Modulus, ksi	Tensile Strength, ksi	% Elong. @ Failure	T_g , °C
Amicure PACM/ Tactix 123	15 min at 70 °C, 120 min at 150 °C	365	11.6	7.2	169
Amicure PACM/ D.E.R. 383	15 min at 70 °C, 120 min at 150 °C	345	11.2	7.3	166
Amicure PACM/ Epon 826	15 min at 70 °C, 120 min at 150 °C	350	11.0	6.7	166
Ancamine 2167/ Tactix 123	15 min at 70 °C, 120 min at 150 °C	375	11.8	6.6	167
Ancamine 2167/ D.E.R. 383	15 min at 70 °C, 120 min at 150 °C	350	11.6	7.2	167
Ancamine 2167/ Epon 826	15 min at 70 °C, 120 min at 150 °C	377	11.3	6.7	161

TABLE 3: IMPACT OF CURE SCHEDULE ON THERMAL AND MECHANICAL PERFORMANCE

Formulation	Cure Schedule	Tensile Modulus, ksi	Tensile Strength, ksi	% Elong. @ Failure	T_g , °C
Amicure PACM/ Tactix 123	15 min at 70 °C, 30 min at 100 °C	355	12.1	6.7	122
Amicure PACM/ Tactix 123	15 min at 70 °C, 60 min at 100 °C	385	12.3	6.7	125
Amicure PACM/ Tactix 123	15 min at 70 °C, 120 min at 150 °C	365	11.6	7.2	169
Ancamine 2167/ Tactix 123	15 min at 70 °C, 30 min at 100 °C	432	12.4	5.8	121
Ancamine 2167/ Tactix 123	15 min at 70 °C, 60 min at 100 °C	423	12.4	6.2	125
Ancamine 2167/ Tactix 123	15 min at 70 °C, 120 min at 150 °C	375	11.8	6.6	167

IMPreS List of Resins Systems

3-9-95

1. Tactix 123 resin, 40 lb.
2. Epon resin 9472, 8 lb.
3. Epon 826 resin, 45 lb.
4. Epon 862 resin, 30 lb.
5. Epon 9405 resin, 8 lb.
6. Epon 9470, 1/4 lb.
7. Epon 3140 curing agent, 40 lb.
8. Epon 3140 curing agent, 40 lb.
9. Epi-cure curing agent W, 35 lb.
10. Ancamine 2167 curing agent, 40 lb.
11. Amicure PACM curing agent, 40 lb.

APPENDIX G—MODEL VALIDATION EXPERIMENTS - COMPOSITE PERFORMANCE

Text provided by Tommy Guess.

Composite fabrication carried out by Tom Bennett.

Composite testing carried out by Tommy Guess and Mark Stavig.

TENSILE PROPERTIES OF GLASS FABRIC AND MAT COMPOSITES FABRICATED BY THE RESIN TRANSFER MOLDING (RTM) PROCESS

Tommy Guess & Mark Stavig
(September 1995)

INTRODUCTION

The purpose of this report is to document the results of tensile tests on two composite materials processed by the resin transfer molding (RTM) process. These experiments were performed to support the micromechanics modeling portion of the IMPReS program. In the RTM process for fabricating composites, a liquid resin is injected into the cavity of a closed mold that contains a preform of the fiber reinforcement. Glass fabric and glass mat preforms and an epoxy resin were used in the composite plates supplied for testing.

MATERIALS AND FABRICATION

The two composite plates were fabricated by Tom Bennett, 8714. One plate contained an E-glass fabric preform, the other an A-glass mat preform and both were injected with Epon 862/W epoxy (Shell Epon resin 862 and EPI-CURE W curing agent mixed in a weight ratio of 100:26.4). The density, modulus and strength of the three constituent materials are listed in Table 1.

Table 1. Constituent properties.

MATERIAL	DENSITY (g/cc)	MODULUS (10 ⁶ psi)	STRENGTH (psi)
A-Glass	2.50	10.0	-----
E-Glass	2.54	10.6	500,000
862/W Epoxy ¹	1.20	0.45	12,000

¹ Shell Epon Resin 862 with EPI-CURE W curing agent (100/26.4 by weight mix ratio); cured for 12 hours at 165°F. Elastic properties epoxy are estimated using manufacturer's data for 250°F cure.

The E-glass fabric was obtained from JPS Glass Fabrics; it's designation is JPS CONFORM[®] FABRIC, Style 7791/Z-6040. This fabric contains equal amounts of fiber in the warp and fill (0°/90°) directions and its unique weave allows up to 38% fabric bias stretch and compression. The fibers have a Volan L finish (sizing) to enhance adhesion to epoxy.

The glass mat preform material, supplied by NICOFIBERS, is called CONFORMAT N-751. It is a continuous strand A-glass mat consisting of 80% strands and 20% monofilaments. The mat is held together with 6% by weight polyester resin binder and a light weight surface veil. The distribution of the reinforcement is essentially uniform in the plane of the mat; this should produce a composite with isotropic in-plane elastic properties.

Two composite plates were processed in a closed mold with a 12.5 x 12.5 x 0.25 inches cavity. A fabric preform was placed in the cavity, liquid epoxy resin was injected and the plate was cured. Details of the processing of the two plates are listed below.

Plate F (fabric preform): This plate was processed 6/29/95.

1. 731 grams of JPS CONFORM E- glass fabric, Style 7791 placed in the mold cavity. This weight of fabrics translates to a theoretical fiber volume of 45%, assuming a plate thickness of 0.25 inch.
2. The mold was preheated to 180°F, a 25 in/Hg vacuum was pulled on the mold for 5 minutes prior to start of resin injection and the vacuum was held for 15 seconds into the injection. The resin was degassed and heated to 160°F. Two 375 cc shots of resin, with a total fill time of about 600 seconds, were required to fill the mold. Pressure in the mold reached 35 psi. By the end of the injection cycle the mold had cooled to 160°F.
3. The mold was placed on its end and the resin was injected into the panel from the lower right corner. Air became trapped near the center of the panel; this air was vented via an overflow outlet located at the center of the mold. Vacuum was maintained for 10 minutes after the injection cycle was completed.
4. The panel was cured for 12 hours at 165°F.

Plate M (mat preform) This plate was processed 8/3/95.

1. 519 grams of NICOFIBERS' CONFORMAT N-751, A-glass mat was placed in the mold cavity. This weight of fabrics translates to a theoretical fiber volume of 32%, assuming a plate thickness of 0.25 inch.
2. The mold was preheated to 180°F, a 25 in/Hg vacuum was pulled on the mold for 5 minutes then turned down to 9 in/Hg for the start and duration of the resin injection cycle. The resin was degassed and heated to 160°F. Two 375 cc shots of resin, with a total fill time of about 600 seconds, were required to fill the mold. Pressure in the mold ranged between 60 and 90 psi. By the end of the injection cycle the mold had cooled to 160°F.
3. The mold was placed on its end and the resin was injected into the panel from the vent located on the vertical center line 1.5 inches from the bottom edge of the panel.
4. The panel was cured for 12 hours at 165°F.

EXPERIMENTAL PROCEDURES AND RESULTS

Plate thicknesses and density

The composite plates were measured for thickness and density. Even though the mold cavity had a depth measurement of 0.25 inch, the RTM plates were thicker and of non-uniform thickness. This is probably the result of bowing of the mold faces due to the pressure occurring during the fill process; recall the mold pressure reached 35 psi in the fabric plate and 90 psi in the mat plate. Thicknesses of Plate F (fabric preform) ranged between 0.293 and 0.360 inch (average of about 0.31 inch), and between 0.278 and 0.336 inch (average of about 0.30 inch) for Plate M (mat preform). The plates were thinner toward the edges and thicker toward the center. These variations in plate and, therefore, specimen thicknesses mean that densities and material properties are nominal values based on estimated average thicknesses.

Nominal measured densities, based on plate and individual specimen weights and estimated volumes, are 1.72 g/cc for the fabric and 1.53 g/cc for the mat composites. This corresponds to fiber volume fractions of 0.36 and 0.27, respectively. On the other hand, theoretical densities, based on the known weights of glass preforms and a plate thickness of 0.25 inch, are 1.80 g/cc and 1.62 g/cc for the fabric and mat composites, respectively. Note that the actual densities are significantly lower than the theoretical densities, a natural result of thicker than expected plates.

Tensile Tests

Flat dogbone tension specimens were machined to final nominal dimensions of 10 inches length and 0.85 inch width. In the reduced-size gage section the width was 0.75 inch and length was 2.75 inches. Specimens were from 3 orientations in plate: the 1-direction, 2-direction and 45°-direction. The 1-direction coincides with the horizontal axis and the 2-direction with the vertical axis of the composite plate as it was being resin filled during processing. These two directions also coincide with the warp and fill directions (0°,90°) of the fabric preform.

Specimens were instrumented with a 2.0-inch extensometer in the gage section to measure strain; a biaxial strain gage was used to measure Poisson's ratio. Testing procedures followed the guidelines in *ASTM D-638, the Standard Method of Test for Tensile Properties of Plastics*. Tensile loads were introduced into the specimens at a crosshead speed of 0.20 inch/minute by means of wedge grips with serrated faces using a screw-driven Model 1125 Instron test machine. All tests were performed at room temperature with all specimens loaded to failure.

Typical stress strain responses are shown in Figures 1 and 2; values of initial elastic modulus, Poisson's ratio and stress at specimen failure are listed in Table 2.

Fig. 1. Typical tensile stress-strain responses of Plate F specimens.

Fig. 2. Typical tensile stress-strain responses of Plate M specimens.

Table 2. Average tensile properties of RTM plates.

	PLATE F E-GLASS FABRIC	PLATE M A-GLASS MAT
NOMINAL DENSITY (g/cc)	1.72	1.53
MODULUS (10^6 psi)		
1-Direction, E_1	2.9 (2)	1.6 (2)
2-Direction, E_2	2.7 (4)	1.5 (4)
45°-Direction, E_{45}	1.4 (3)	1.5 (3)
POISSON'S RATIO		
1-Direction	0.15 (2)	0.37 (2)
2-Direction	0.15 (2)	0.37 (2)
45°-Direction	0.50 (1)	0.31 (2)
STRENGTH (ksi)		
1-Direction	37 (2)	10 (2)
2-Direction	28 (4)	17 (4)
45°-Direction	19 (3)	16 (3)

Notes:

1. Number in parenthesis is the number of data points used to calculate average values .
2. Plate F 1-direction and 2-direction specimens failed in the grip region; therefore, these values are lower bounds on the true strength of the composite. However, the Plate F 45°-direction specimens and all of the Plate M specimens failed in the gage section; these are valid strengths. There was some delamination in the Plate M 1-direction specimens, whereas, the other Plate M specimens had no delamination.

Note that the 1- and 2-direction moduli of the fabric composite are essentially equal. This is an expected result for a fabric composite having equal amounts of fiber reinforcement in the warp and fill directions. Strength values in these two directions are lower bounds and not the actual strength because the specimens broke under the grips and not in the gage section. The off angle properties of the fabric composite are reduced as evidenced by the reduction of modulus and strength in the 45° direction. On the other hand, the mat composite had equal moduli in the three directions tested; this is the isotropic elastic response anticipated. For unknown reasons, the strength of the 1-direction mat specimen was significantly lower than the strengths in the other two directions and the failure mode was different. There was some delamination between the mat layers in the 1-direction specimens, but not in the 2- and 45°-direction tensile test coupons.

Prediction of Modulus

In this section, the estimation of the Plate F fabric composite elastic properties will be illustrated using micromechanics rule-of-mixtures and laminated plate theory. Due to uncertainties in actual fiber volume and thickness variations within a single specimen, and from specimen to specimen, this exercise is not expected to produce exact agreement between predicted and experimental moduli.

Fabric/Epoxy Composite-- Unidirectional properties of an E-glass/epoxy single layer lamina can be estimated using rule-of-mixture equations [1], with input of fiber and resin properties and

fiber volume. The properties of a layered composite consisting of layers of unidirectional lamina can then be calculated using laminated plate theory [2], with input of the lamina properties and the orientation of the individual layers in the composite. For this example, a (0°/90°) layup of unidirectional layers is assumed to represent the fabric composite (Ann Sastry's work for the IMPReS programs discusses other models that could be utilized, some of which account for fabric construction).

Rule-of-mixtures equations for the longitudinal and transverse moduli of a unidirectional layer are

$$E_L = E_f v_f + E_r v_r \quad (1)$$

$$E_T = E_f E_r / (E_f v_r + E_r v_f) \quad (2)$$

where E is the modulus, v is the volume fraction and the subscripts f and r denote fiber and resin, respectively. Similar equations are available for ply shear modulus and Poisson's ratio. For example, Eqs. (1) and (2) yield $E_L = 4.51 \times 10^6$ psi and $E_T = 1.02 \times 10^6$ psi for a fiber volume fraction of $v_f = 0.4$ and the fiber and epoxy resin properties in Table 1.

Once the elastic properties of a single ply are calculated, the moduli of the crossply laminate can be predicted using laminated plate theory [2] (equations and calculations will not be shown here). Because the fiber volume is not known exactly for the fabric composite (it falls somewhere between 0.35 and 0.45), calculations were made for three different values of v_f , namely, 0.35, 0.40 and 0.45. The results of the composite moduli calculations for the 1-, 2-, and 45°-directions are plotted in Figure 3 as a function of v_f . Also shown in Figure 3 are the experimental values of Plate F moduli.

Figure 3. Predicted moduli of a crossply E-glass/epoxy composite as a function of glass fiber volume fraction. Calculations based on rule-of-mixtures and laminated plate theory. Experimental data shown are from Plate F fabric composite specimens of unknown fiber volume fraction.

Inspection of Figure 3 shows that the experimental and predicted moduli in the 1- and 2-directions are in good agreement, provided the fiber volume fraction of Plate F is about 0.40. On

the other hand, agreement between experimental and predicted 45°-direction moduli requires that the plate fiber volume fraction be about 0.45. These results demonstrate that the rule-of-mixtures and laminated plate theory are useful tools for predicting the elastic properties of composites. Better agreement between experimental and predicted values are expected when more realistic rule of mixtures equations are used to model the fabric construction and when the fiber volume fraction of the material is known and is uniform throughout the plate.

Mat/Epoxy Composite--No attempt was made to predict the modulus of the Plate M glass mat composite because we were not able to quickly put our hands on a micromechanics strength-of-materials model for random planar mat composites.

SUMMARY

Tensile tests were performed on E-glass fabric and A-glass mat reinforced composite materials fabricated by the RTM process. Moduli, Poisson's ratios and strengths from three specimen orientations were measured for both materials. Experimental values of the fabric composite's moduli were compared to predicted moduli that were calculated using rule-of-mixtures micromechanics models and laminated plate theory.

REFERENCES

- [1]. Robert M. Jones, *MECHANICS OF COMPOSITE MATERIALS*, SCRIPTA Book Company, Washington, D.C., 1975, pp. 90-92.
- [2]. *ibid*, pp. 147-187

APPENDIX H—GENERAL BIBLIOGRAPHY

Assembled by Linda Domeier and Greg Jamison.

General Books (RTM, Composites, High Performance Polymers, etc.)

"High Performance Thermosets: Chemistry, Properties, Applications," S. C. Lin and E. M. Pearce
Carl Hanser Verlag, NY, 1994. ISBN 1-56990-155-4

"Advanced Thermoplastic Composites: Characterization and Processing," H.-H. Kausch, Ed. Carl
Hanser Verlag, NY, 1993. ISBN 3-446-17028-6

"Fundamental Principles of Fiber Reinforced Composites," Ashbee, K., Technomic Publishing Co.
Lancaster, PA, 1993. ISBN 0-87762-923-4

"Reaction Polymers: Chemistry, Technology, Applications, Markets," W. F. Gum, W. Riese, H.
Ulrich, Eds. Carl Hanser Verlag, NY, 1992. ISBN 3-446-15690-9

"High Performance Polymers: Structure, Properties, Composites, Fibers," E. Baer and A. Moet,
Eds. Carl Hanser Verlag, NY, 1991. ISBN 3-446-15676-3

"Polymeric Materials and Processing: Plastics, Elastomers, and Composites," Charrier, J.-M., Carl
Hanser Verlag, NY, 1991. ISBN 0-19-520854-4

"Composite Materials Technology: Process and Properties," P. K. Mallick, S. Newman, Eds. Carl
Hanser Verlag, NY, 1990. ISBN 3-446-15684-4

General Articles

"RTM Research Took Center Stage at Composite Conference," *Plastics Technology*, Feb. 1995.

M.C. Gabriele, "Chrysler's Viper is Driving Innovation in RTM," *Plastics Technology*, March,
1994, p. 38

K. Fisher, "RTM and Core Materials Offer Product Advances," *High Performance Composites*,
Sept./Oct., 1994, p. 23.

D. Stover, "Designing for RTM," *High Performance Composites*, Sept./Oct. 1993, p. 54.

G. Elber, "Resin Transfer Molding: Tips for Successful Application," *Advanced Composites*,
Sept./Oct. 1993, p. 26.

"RTM Work Takes Shape in Advanced Composites," *Advanced Composites* March/Apr. 1992, p.
39.

Concurrent and Smart Manufacturing

B.Frye, "Resin Transfer Molding: The Infostructure Barrier/Opportunity," 26th Int. SAMPE Tech.
Conf. Oct. 17-20, 1994, p. 417.

D.E. Kranbuehl, D. Hood, J. Rogozinski, W. Limburg, A.C. Loos and J. MacRae, "Smart
Manufacturing for Resin Transfer Molding of Advanced Fiber Architecture Preforms," *Materials
Technology*, 1994, 82, p.18.

G. Hasko, H.B. Dexter, A. Loos and D. Kranbuehl, "Application of Science-Based RTM for
Fabricating Primary Aircraft Structural Elements," *J. Advanced Materials*, 1994, 26, p.9.

R. Pitchumani, P.A.Schwenk, V.M.Karbhari, J.F.Ramsay and T.D.Claar, "A Knowledge-Based Decision Support System for the Manufacture of Composite Preforms," 25th Int. SAMPE Tech. Conf. Oct. 26-8, 1993, p. 1069.

A. Strombeck, "Optimization of the Resin Transfer Moulding Process for Advanced Composites," Proc. Int. Conf. Composite Materials, 9th, 1993, 3, p. 497.

A. C. Loos and D. E. Kranbuehl, "Intelligent Processing of Advanced Composite Materials," Winter Ann. Meeting of Am. Soc. Mech. Eng., Nov. 25-30, 1990, p. 15.

In Situ Sensors

D.E. Kranbuehl et al, "In Situ Sensor Monitoring and Intelligent Control of the Resin Transfer Molding Process," Polymer Composites, 1994, 15, p. 299.

S.M. Milkovich, R.I. Altkorn, R.H. Haidle, M.J. Neatrou and J.M. Fildes, "In Situ Sensors for Intelligent Process Control for Fabrication of Polymer-Matrix Composite Materials," SPIE, 1994, 2191, p. 349.

D.E. Kranbuehl, P. Kingsley, S. Hart, G. Hasko, B. Dexter and A.C. Loos, "Sensor-Model in Situ Monitoring and Intelligent Control of the Resin Transfer Molding Composite Cure Process," Macromolecules, 1992, p. 55.

Preform Technology

S.H. Ahn, W.I. Lee and G.S. Springer, "Measurement of the Three-Dimensional Permeability of Fiber Preforms Using Embedded Fiber Optic Sensors," J. Composite Materials, 1995, 29, p. 714.

C.D. Rudd, V. Middleton, M.J. Owen, A.C. Long and P. McGeehin, "Design, Processing and Performance of Structural Preforms," Materials and Manufacturing Processes, 1995, 10, p.89.

R. Gauvin, A. Kerachni and B. Fisa, "Variation of Mat Surface Density and Its Effect on Permeability Evaluation for RTM Modeling," J. Reinf. Plast. and Comp. 1994, 13, 371.

L. Fong and L.J. Lee, "Preforming Analysis of Thermoformable Fiber Mats - Preforming Effects on Mold Filling," J. Reinforced Plastics and Composites, 1994, 13, p. 637.

Z. Cai and A.L. Berdichevsky, "Estimation of the Resin Flow Permeability of Fiber Tow Preforms Using the Self-Consistent Method," Polymer Composites, 1994, 15, p. 240.

K.M.Pillai, T.L. Luce, V.M. Bruschke, R.S. Parnas and S.G. Advani, "Modeling the Heterogeneities Present in Preforms During Mold Filling in RTM," 25th Int. SAMPE Tech. Conf. Oct. 26-28, 1993, p. 279.

D. Weyrauch and W. Michaeli, "A New Preforming Technology for RTM and SRIM," Ann. Tech. Conf. SPE, 1992, 1, p. 761.

D. Stover, "Near Net Preforms and Processes Take Shape" Advanced Composites July/Aug. 1992, p. 38.

Flow Studies (Modeling and Experimental)

G. Di Vita, F. Ferraro and P. Perugini, "Development of Process Simulation Models for Composite Technology," Materials and Manufacturing Processes, 1995, 10, p. 103.

Wen-Bin Young, "Thermal Behaviors of the Resin and Mold in the Process of Resin Transfer Molding," J. Reinforced Plastics and Composites, 1995, 14, 310.

D.A. Steenkamer, S.H. McKnight, D.J. Wilkins and V.M. Karbhari, "Experimental Characterization of Permeability and Fibre Wetting for Liquid Moulding," J. Materials Science, 1995, 30, p. 3207.

W.B. Young and C.W. Tseng, "Study on the Pre-heated Temperatures and Injection Pressures of the RTM Process," J. Reinforced Plastics and Composites, 1994, 13, p. 467.

X. Xia, C. DiSanto, M. Xie, and S. Hoa, "Experimental Verification of Scale Relations in Mold Filling Simulation in Resin Transfer Molding," 26th Int. SAMPE Tech. Conf. Oct. 17-20, 1994, p. 172.

S.A. Wymer and R.S. Engel, "A Numerical Study of Nonisothermal Resin Flow in RTM with Heated Uniaxial Fibers," J. Composite Mater. 1994, 28 (1), 53.

N.R. Anturkar, "A Model of Advancing Flow Front in RIM," Polymer Engineering and Science, 1994, 34, p. 1450.

Yu-Wen Lo, D. D. Reible, J.R. Collier and Cheng-Ho Chen, "Three Dimensional Modeling of Reaction Injection Molding. Parts I and II," Polymer Engineering and Science, 1994, 34, pp. 1393 and 1401.

"Low-Cost Injection and Compression Mold-Filling Analysis," Technology Newsfocus, Plastics Technology, Aug. 1994, p. 13.

W. Zhang and S.G. Advani, "Heat Dispersion Effects in Stationary Fiber Beds," Mechanics in Mater. Processing and Manuf. 1994, 194, 335.

Y. Liu, C. Ganesh and J.P.H. Steele, "The Kinetic Characteristics of a Typical Epoxy Resin System," 26th Int. SAMPE Tech. Conf. Oct. 17-20, 1994, p. 561.

R. Leek, G. Carpenter, A. Rubel, T. Donnellan, and F. Phelan, "Simulation of Edge Flow Effects in Resin Transfer Molding," 25th Int. SAMPE Tech. Conf. Oct. 26-28, 1993, p. 233.

A.W. Chan and R.J. Morgan, "Tow Impregnation During Resin Transfer Molding of Bidirectional Nonwoven Fabrics," Polymer Composites, 1993, 14 (4), 335.

S.R. White and H.T. Hahn, "Cure Cycle Optimization for the Reduction of Processing-Induced Residual Stresses in Composite Materials," J. Composite Materials, 1993, 27, 1352.

G.D. Smith and A. Poursantip, "A Comparison of Two Resin Flow Models for Laminate Processing," J. Composite Mater. 1993, 27 (17), 1695.

J. Summerscales, "A Model for the Effect of Fiber Clustering on the Flow Rate in Resin Transfer Molding," Composite Manuf. 1993, 4 (1), 27.

F. Trochu, R. Gauvin and D.M. Gao, "Numerical Analysis of the Resin Transfer Molding Process by the Finite Element Method," Adv. Polym. Tech. 1993, 12, (4), 329.

J.M. Kenny, A. Trivisano, J.L. Kardos, and B. Khomami, "Mathematical Modeling of the Resin Transfer Molding of High Performance Composites," 38th Int. SAMPE Sym., 1993, p. 1263

L.W. Hourng and C.Y. Chang, "Numerical Simulation of Resin Injection Molding in Molds with Preplaced Fiber Mats," J. Reinforced Plast. Compos., 1993, 12, p. 1081.

E. Brugnoli, G. D. Di Vita, M. Marchetti, and A. Moscatelli, "Two Dimensional Simulation of Resin Front Advancement in Resin Transfer Molding Process by Use of the Boundary Element Method," *Engineering Systems Design and Analysis*, 1992, 47, (6), p. 39.

Z. Cai and A. L. Berdichevsky, "The Development of Process Modeling for Resin Transfer Molding," *Proc. Int. Conf. Transp. Therm. Process*, 1st Ed., S. I. Guceri, Ed. 1992, p. 1239.

S. Raman, A. Shaikh and P. H. Cohen, "A Mathematical Model For Tool Temperature Sensing," *Comp. Methods in Mater. Processing* 1992, 39, 181.

K. N. Kendall, C. D. Rudd, M. J. Owen and V. Middleton, "Characterization of the Resin Transfer Moulding Process," *Composites Manufacturing*, 1992, 3, p. 235.

T. Nowak and J. Chun, "Three-Dimensional Measurement of Preform Impregnation in Composites Manufacturing," *Composites Manufacturing*, 1992, 3, p. 259.

R. Lin, L. J. Lee and M. Liou, "Non-Isothermal Mold Filling and Curing Simulation in Thin Cavities with Preplaced Fiber Mats," *Intern. Polymer Processing VI*, 1991, 4, p. 356.

Void Formation and Defects

A. W. Chan, and R. J. Morgan, "A Model on Formation of Rod-Like Voids in Fiber Tows," *SAMPE Quarterly*, July, 1993, 24, p. 49.

T. S. Lundstroem, B. R. Gebart and C. Y. Lundemo, "Void Formation in RTM," *J. Reinforced Plast. Composites*, 1993, 12, p. 1339.

W. Michaeli and J. Dyckhoff, "Improvement in the Surface Quality of Structural Components Produced by the RTM Process," *Adv. Compos. '93, Proc. Int. Conf. Adv. Compos. Mater.*, 1993, p. 749

Testing Methods

A. L. Jackson, P. R. Gagnon and S. R. Reeve, "Test Methodology for Evaluating Microcracking in Composite Laminates," *26th Int. SAMPE Tech. Conf.* Oct. 17-20, 1994, p. 765.

F. H. Chang, T. E. Drake, M. A. Osterkamp, R. S. Prowant, J. P. Monchalain, R. Héon, P. Bouchard, C. Padioleau, D. A. Froom, W. Frazier and J. P. Barton, "Laser Ultrasonic Inspection of Honeycomb Aircraft Structures," *Rev. Prog. Quant. Nondest. Eval.* (D. O. Thompson, D. E. Chimenti, Eds.), Plenum, 1993, v. 12, p. 611.

C. Padioleau, P. Bouchard, R. Héon, J. P. Monchalain, F. H. Chang, T. E. Drake and K. I. McRae, "Laser Ultrasonic Inspection of Graphite Epoxy Laminates," *Rev. Prog. Quant. Nondest. Eval.* (D. O. Thompson, D. E. Chimenti, Eds.), Plenum, 1993, v. 12, p. 1345.

Fiber Sizings

G. R. Palmese and V. M. Karbhari, "Effects of Sizings on Microscopic Flow in Resin Transfer Molding," *Polymer Composites*, 1995, 16, p. 313.

G. R. Palmese J. M. Deputy and V. M. Karbhari, "Effects of Sizings on Microscopic Flow Encountered in RTM Processing of E-Glass Fibers," *Proc. 10th Annual ASM/ESD Advanced Composites Conf.* November, 1994, p. 449.

B.K. Larson and L.T. Drzal, "Glass Fibre Sizing/Matrix Interphase Formation in Liquid Composite Moulding: Effects on Fibre/Matrix Adhesion and Mechanical Properties," *Composites*, 1994, 25, p. 711.

G.R. Palmese and V.M. Karbhari, "Effects of Sizings on Microscopic Flow Encountered in RTM Processing," 25th Int. SAMPE Conf. Oct. 26-8, 1993, p. 254.

Resin Materials

J. M. McKillen III, "Process Tolerant Resin Transfer Molding Products," 26th Int. SAMPE Tech. Conf. Oct. 17-20, 1994, p. 423.

L. Boutin, A. Ajji and L. Choplin, "Characterization of Thermosets Used for Resin Transfer Molding Process," 50th Annual Tech. Conf. (ANTEC) - SPE, 1992, p. 2321.

Stark, E. B. et. al., "Resin Transfer Molding (RTM) of High Performance Resins," 35th Int. SAMPE Symp. April, 2-5, 1990, 782.

Composite Properties

C. E. Harris, D. H. Allen and D. C. Lo, "A Mechanics Framework for a Progressive Failure Methodology for Laminated Composites," NASA Tech. Support Package for Tech. Brief LAR-14437, Modeling Progressive Damage in Laminated Composites, May, 1994.

A. Hague, H. Mahfuz, T.X. Yu and S. Jeelani, "Effect of Processing Parameters on Property Changes of Resin Transfer Molded Materials," 25th Int. SAMPE Technical Conf., Oct. 26-8, 1993, p. 305.

V.M. Karbhari, S.G. Slotte, D.A. Steenkamer and D.J. Wilkins, "Effect of Material, Process and Equipment Variables on the Performance of Resin Transfer Moulded Parts," *Composites Manufacturing* 1992, 3 (3), 143.

General Books (RTM, Composites, High Performance Polymers, etc.)

"High Performance Thermosets: Chemistry, Properties, Applications," S. C. Lin and E. M. Pearce
Carl Hanser Verlag, NY, 1994. ISBN 1-56990-155-4

"Advanced Thermoplastic Composites: Characterization and Processing," H.-H. Kausch, Ed. Carl
Hanser Verlag, NY, 1993. ISBN 3-446-17028-6

"Fundamental Principles of Fiber Reinforced Composites," Ashbee, K., Technomic Publishing Co.
Lancaster, PA, 1993. ISBN 0-87762-923-4

"Reaction Polymers: Chemistry, Technology, Applications, Markets," W. F. Gum, W. Riese, H.
Ulrich, Eds. Carl Hanser Verlag, NY, 1992. ISBN 3-446-15690-9

"High Performance Polymers: Structure, Properties, Composites, Fibers," E. Baer and A. Moet,
Eds. Carl Hanser Verlag, NY, 1991. ISBN 3-446-15676-3

"Polymeric Materials and Processing: Plastics, Elastomers, and Composites," Charrier, J.-M., Carl
Hanser Verlag, NY, 1991. ISBN 0-19-520854-4

"Composite Materials Technology: Process and Properties," P. K. Mallick, S. Newman, Eds. Carl
Hanser Verlag, NY, 1990. ISBN 3-446-15684-4

General Articles

"RTM Research Took Center Stage at Composite Conference," *Plastics Technology*, Feb. 1995.

M.C. Gabriele, "Chrysler's Viper is Driving Innovation in RTM," *Plastics Technology*, March,
1994, p. 38

K. Fisher, "RTM and Core Materials Offer Product Advances," *High Performance Composites*,
Sept./Oct., 1994, p. 23.

D. Stover, "Designing for RTM," *High Performance Composites*, Sept./Oct. 1993, p. 54.

G. Elber, "Resin Transfer Molding: Tips for Successful Application," *Advanced Composites*,
Sept./Oct. 1993, p. 26.

"RTM Work Takes Shape in Advanced Composites," *Advanced Composites* March/Apr. 1992, p.
39.

Concurrent and Smart Manufacturing

B.Frye, "Resin Transfer Molding: The Infostructure Barrier/Opportunity," 26th Int. SAMPE Tech.
Conf. Oct. 17-20, 1994, p. 417.

D.E. Kranbuehl, D. Hood, J. Rogozinski, W. Limburg, A.C. Loos and J. MacRae, "Smart
Manufacturing for Resin Transfer Molding of Advanced Fiber Architecture Preforms," *Materials
Technology*, 1994, 82, p.18.

G. Hasko, H.B. Dexter, A. Loos and D. Kranbuehl, "Application of Science-Based RTM for
Fabricating Primary Aircraft Structural Elements," *J. Advanced Materials*, 1994, 26, p.9.

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