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"Design of Fabric Preforms for Double Diaphragm Forming "

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Summary

Resin Transfer Molding (RTM) has the potential of becoming one of the most cost effective ways of producing composite structures since the raw materials used, resin and dry fabric, are less costly than prepregs. Unfortunately these low material costs are offset by the high labor costs incurred downstream to layup the dry fabric into 3 dimensional shapes. To reduce the layup costs, double diaphragm forming is being investigated as a potential technique for creating a complex 3D preform from a simple flat layup.

As part of our effort to develop double diaphragm forming into a production capable process, we have undertaken a series of experiments to investigate the interactions between process parameters, mold geometry, fabric weave, tow size, and the quality of the formed part. The results of these tests will be used to determine the forming geometry limitations of double diaphragm forming and to characterize the formability of fabric configurations. An important part of this work has been the development of methods to measure and analyze fiber orientations, deformation angles, tow spreading, and shape conformation of the formed parts. This paper will describe the methods used to mark the plies, the double diaphragm forming process, the techniques used to measure the formed parts and the calculation of the parameters of interest. The results can be displayed as 3D contour plots. These experimental results have also been used to verify and improve a computer model which simulates the draping of fabrics over 3D mold shapes.

Introduction

One of the major obstacles limiting the expanded use of composite materials is their relatively high cost in comparison to alternative materials such as metals. These costs are attributable to expensive raw materials as well as labor intensive manufacturing processes. To develop new processes which reduce the cost of manufacturing composite structures, it is important to understand first the costs in current manufacturing processes. However, this cost-based design approach presents a problem, because the costs of composites manufacturing processes are not well understood. In addition, there are numerous combinations of raw materials and processing techniques that can be combined to manufacture a particular part each with its own structural and cost benefits. Due to the variety and complexity of these processes, it is important to use cost analysis tools in the early stages of process development efforts [1]. By using cost analysis tools, not only can the most cost effective current processes be identified but the cost centers for the processes can also be located. The results of such analysis can then be used to target and to set specifications for the development of new improved processes.

Cost analysis has shown that Resin Transfer Molding (RTM) holds promise for cost effective composite structure manufacturing since the raw materials required, dry fabric and resins, are less costly than prepregs [2]. These low material costs are currently offset, however, by the labor intensive downstream operations required to layup the three-dimensional fiber preforms. To reduce RTM preform layup costs, double diaphragm forming is being investigated as a cost effective technique for producing three-dimensional preforms.

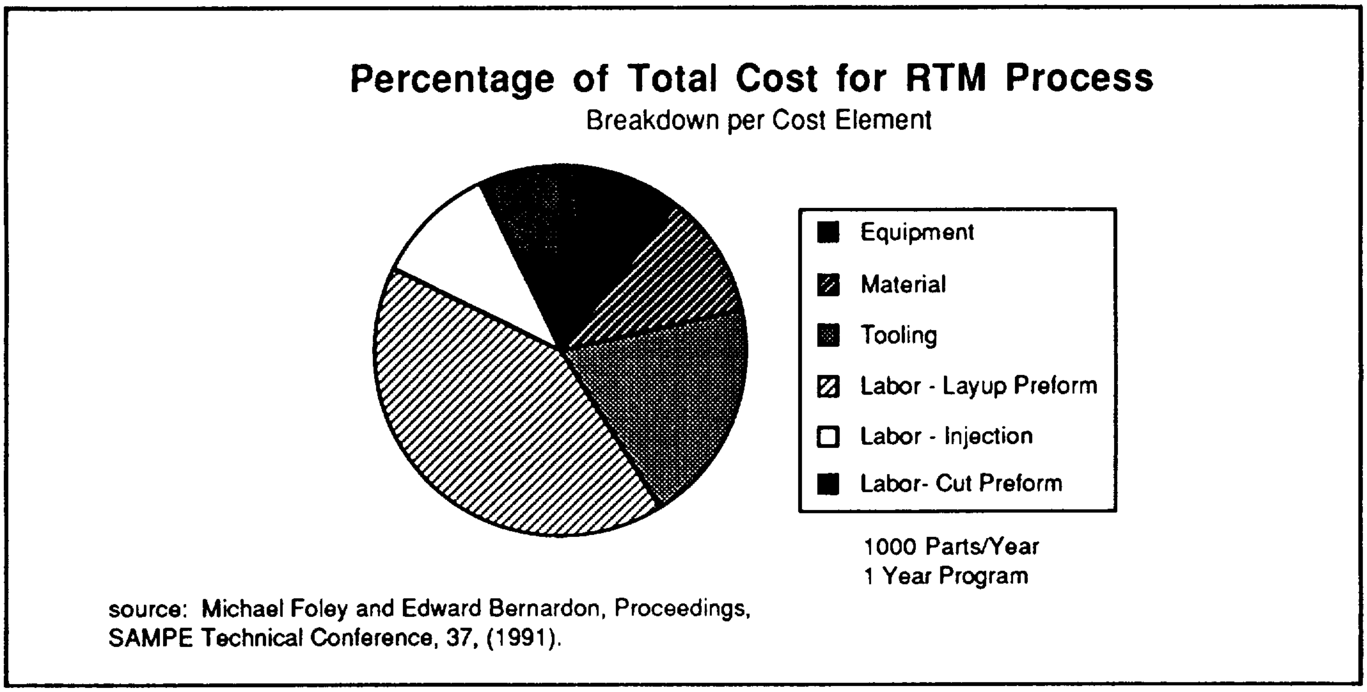
In this paper, we will first describe the cost motivation for development of the double diaphragm preforming process. Then we will describe a set of methods that are being used to measure and analyze fiber orientations, deformation angles, tow spreading and shape conformation of formed parts. Finally we will show how the results from experiments based on the described methods were also used to verify and improve a computer simulation that drapes fabrics over 3D contours. This simulation will serve as a basis for a design tool that will help predict fiber orientations and other important properties in formed parts.

Cost Analysis

In this section we will describe the results of the cost analysis that motivated the development of the double diaphragm preforming process. In the initial cost study, several state-of-the-art manufacturing processes, including filament winding, automatic tape laying, thermoplastic press forming and resin transfer molding, were compared. (See [2] for details of the study.) For the specific family of part geometries considered in the study, resin transfer molding was the most cost effective process examined at all production volumes and was chosen as a starting point for further process development.

RTM's main advantages over the other processes considered in the study are that it uses the lowest cost constitutive materials possible (fiber and resin), it has a relatively short cycle time, and that a high degree of geometric complexity and part integration is possible. Also, because injection pressures are low (10-80 psi), equipment costs are typically small (~$25-50K).

A breakdown of RTM cost components is shown in Figure 1. This data was obtained by averaging an empirical database of actual costs for a number of RTM parts currently in production in low and mid-volume aerospace applications.



source: Michael Foley and Edward Bernardon, Proceedings, SAMPE Technical Conference, 37, (1991).

Figure 1

Figure 1 indicates that the largest percentage (≈40%) of the cost of the traditional RTM process lies in preparation of the fabric preform. The trends identified here are based on parts of small to medium size and of low to medium complexity. The contribution of major cost components such as preform preparation will become even larger as parts become larger and more complex.

As a result of this analysis, it became clear that to improve the cost effectiveness of RTM, alternative methods of preform preparation, such as double diaphragm forming, must be investigated.

Double Diaphragm Forming

A schematic of a double diaphragm former for preform preparation is shown in figure 2. The two-dimensional dry fabric preform is trapped between two elastomeric diaphragms mounted in frames. A vacuum is drawn between the diaphragms through a breather strip to hold the preform during the forming process. The preform/diaphragm sandwich is situated over a vacuum forming chamber containing the part mold. A vacuum is drawn inside the chamber to shape the preform diaphragm sandwich to the mold.

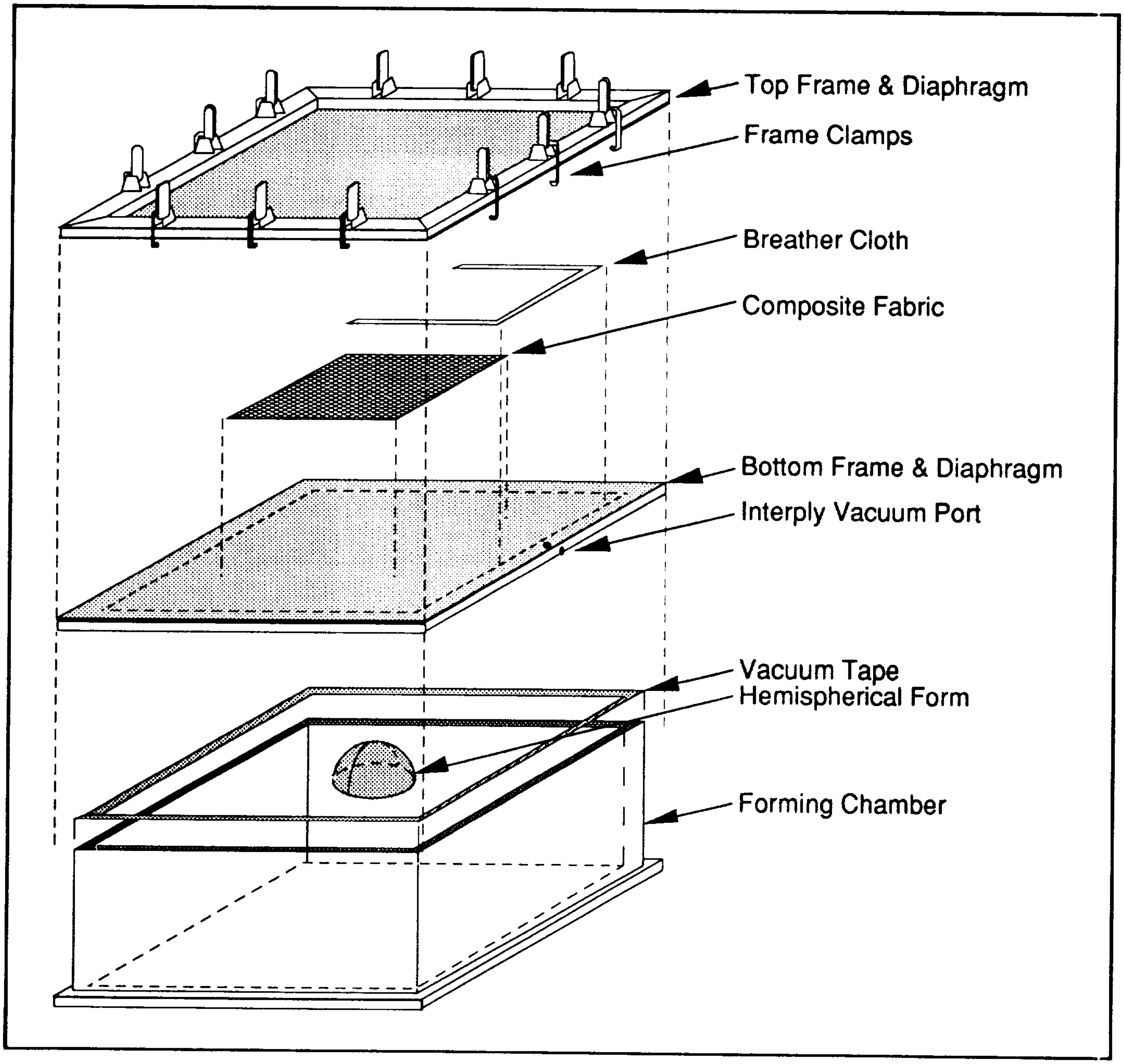


Figure 2. Double Diaphragm Former

The analysis described above indicated the primary RTM cost component is the three-dimensional layup of the fiber preform. The greatest advantage of the double diaphragm forming process is that all preform layup is completed in the flat, thus eliminating costly three-dimensional layup. Since the time required for flat layup is small relative to three-dimensional layup, layup labor costs are greatly reduced. In addition, automated techniques for preparing flat layups are more easily developed than those for complex 3D geometries and the diaphragms can be used to support plies during transport. The diaphragms maintain constant contact with the preform, inhibiting out of plane buckling or wrinkling, and because the tool is not in contact with the fabric, the preform can be removed easily after forming. As a result, this three-dimensional forming process is very repeatable and tuning preform shapes can significantly reduce post trimming operations, thereby increasing material utilization and reducing scrap costs.

Double diaphragm forming has several advantages over single diaphragm forming and hand layup since the two diaphragms inhibit out of plane buckling and wrinkling thus improving part formability. The diaphragms can also support plies during transport and the tool is not in contact with the fabric facilitating the removal of the part after forming.

Although double diaphragm forming reduces preform layup time, the complexity of preforms that can be manufactured are not as geometrically complex as those possible with hand layup. The geometric limits of the forming process are a function of the former design (diaphragm stiffness, elongation, etc.) as well as properties of the preform itself. To understand and extend the complexity envelope of the double diaphragm forming process, experimentation has begun to investigate the effects of various preform material properties on the forming limits of double diaphragm forming. As we better understand the forming capabilities of preform materials, the size and complexity of manufacturable parts will increase. As a result, smaller preforms could be consolidated, reducing not only handling during the layup process, but also eliminating preform joining operations.

Test Plan

After the initial try out of the diaphragm forming equipment and determination of suitable process parameters, a series of experiments was performed using two different molds, a 4 inch hemisphere and a 4 inch cube with 1/2 inch corner radii, both illustrated in Figure 3. The four test materials were each draped in several orientations under various initial conditions. Differences in formability as influenced by fabric weave, tow size and drape configuration were examined and quantified where possible.

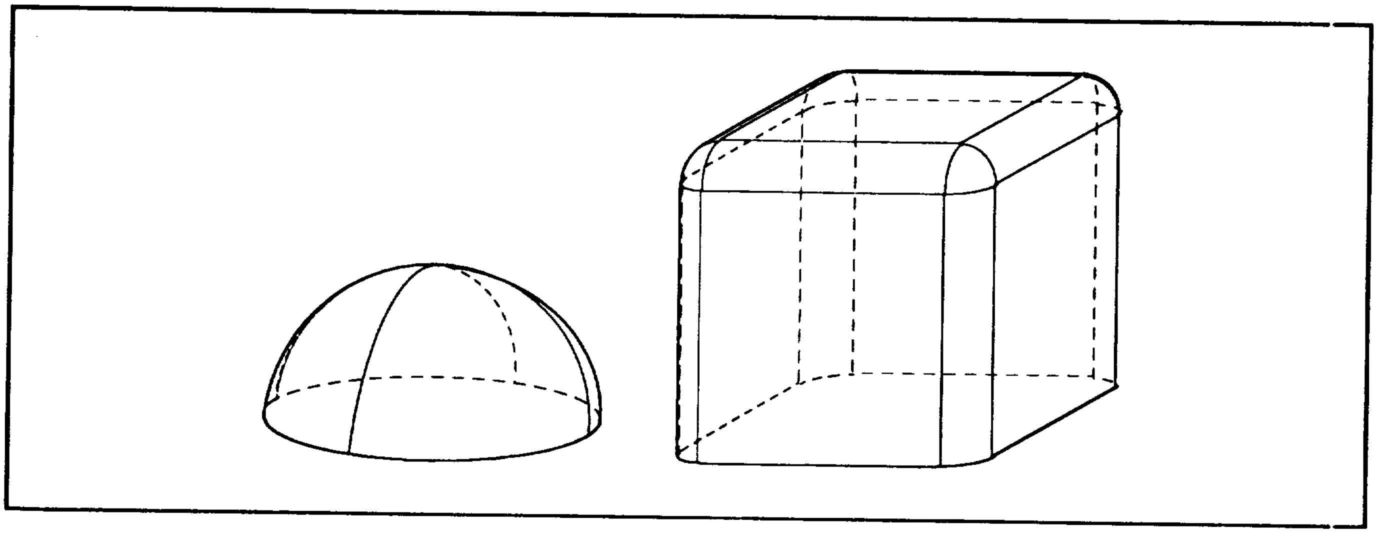


Figure 3. Composite preform mold shapes

To quantify the results, a method was devised to measure the deformation parameters of interest, including deformation angle, spreading and shape conformation. The results of these measurements can be displayed as 3 dimensional contour plots and compared directly to the results of the Draper simulation of the fabric lay up process.

The insights we make into the mechanics of diaphragm forming will guide the design of the next generation of formers. Although these tests are being performed on a double diaphragm former, they are contributing significantly to our knowledge of the deformation of woven fabric, including the interaction of part geometry and fabric material and weave.

Experimental Procedure

The process starts by marking the composite fabric with a grid pattern that will later guide the measurement of the part. To achieve a uniform grid, a silkscreen with small dots in a 0.5" grid pattern was used to mark batches of material before testing. After several tests an ink and pattern were found which adhered to the materials but did not interfere with the forming process. After marking, the plies were cut to size, 8" square for the hemisphere and 12" square for the cube.

Next, the ply is placed on the bottom diaphragm and sprayed with a starch solution that will dry and hold the preforms shape. The starch solution contains poly-vinyl-alcohol dissolved in hot water and diluted with isopropyl alcohol. The breather cloth is then positioned and the top diaphragm clamped in place.

To begin forming, a vacuum is pulled between the diaphragms, then a vacuum is drawn in the forming chamber which pulls the diaphragm-ply sandwich down over the mold. When forming has ceased, a bank of infrared lamps is used to drive some of the volatiles in the starch. After the ply has begun to dry, air is forced between the diaphragms, the top diaphragm removed, and the drying finished. After the preform is completely dry, the part can be removed and the vacuum in the forming chamber released.

The Laser Coordinate Measurement System (LCMS) developed at CSDL was used to digitize the grid points on each part, capturing the three dimensional coordinates. The grid dots were located by hand with a pressure sensitive laser probe. The coordinates were recorded in an ASCII character file and then converted into Patran neutral file format and viewed using Patran on a Sun Sparc station. The data was screened for correctness (i.e., removal of double data points) and the refined model was stored as a second Patran neutral file. This file was then passed through a program that calculated the deformation angle and x and y (or warp and weft) spreading.

The deformation angle is defined as the smallest included angle in the rectangle defined by four grid points. In Figure 4 these points are labeled A, B, C and D. The deformation angle for corner A is given by the dot product of two vectors AB and AD. The angle is calculated for each corner and the smallest angle is the deformation angle recorded for that quadrangle.

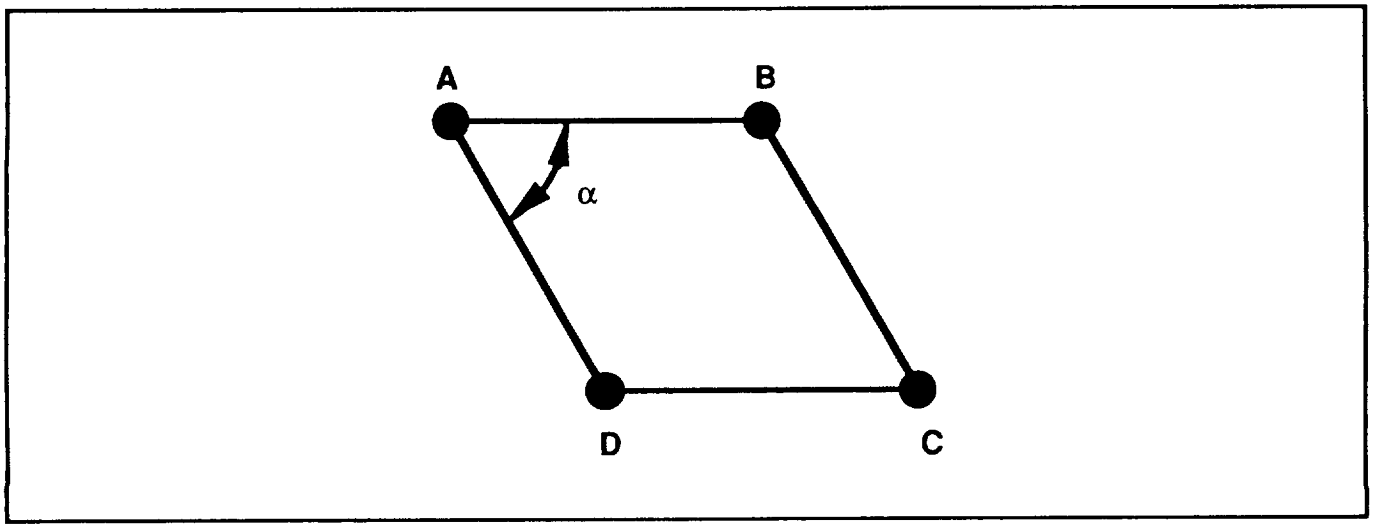


Figure 4. Definition of measured parameters

Spreading is defined as the ratio of the overall length of a side divided by the original length. The x and y directions correspond to the warp and weft of the ply which were orthogonal prior to forming. In figure 4 the X direction spreading would be the distance from point A to B divided by 0.5", the original distance between grid points.

After preprocessing the inspection data can be shown as a series of Patran generated 3D color contour surface plots of deformation angle and spreading in the x and y directions. An example plot of a formed hemisphere is shown in figure 5.

The digitized data can also be used to measure the degree of conformation to the desired shape. The distance from the digitized points to the ideal surface (that of the mold) can be determined and the results displayed in the form of a 3 dimensional contour plot. The volume of the space between the formed part and the mold could also be calculated. These techniques could result in effective quality control methods for double diaphragm and other types of preform forming.

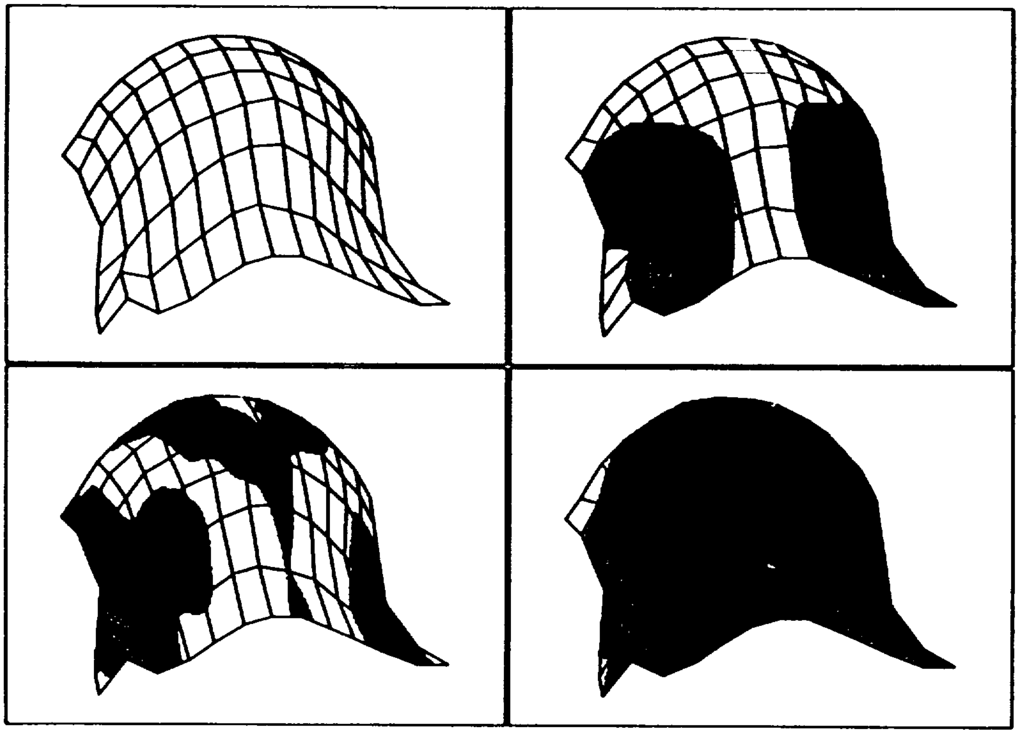


Figure 5. Four views of data derived by digitizing a grid of points on an experimental composite preform. From upper left, wire frame representation of data, contour plot of deformation angle, and contour plots of spreading in the x and y directions respectively.

Simulation of fabric draping

A drape simulation code based on work done at the University of Delaware's Center for Composite Materials [3] was used to support the diaphragm forming experiments. Figure 6 shows the results from the drape simulation over a filleted hemisphere. When the simulation plot is scaled properly and compared directly with the experimental deformation angle plot in figure 5, the simulation is shown to have accurately predicted both the location and magnitude of fabric deformation. The simulation will be extended and modified based on the results of the experiments.

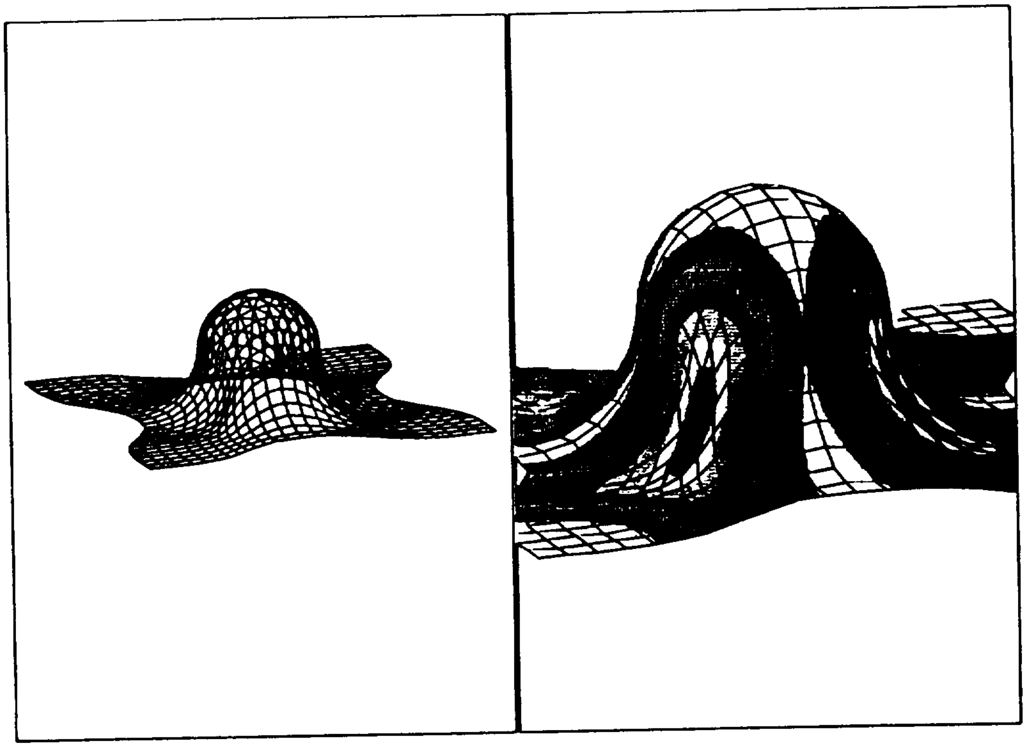


Figure 6. Two views of the results from the drape simulation over a filleted hemisphere. On the left, a wire frame representation of data, on the right a contour plot of deformation angle.

Conclusion

Resin transfer molding (RTM) is a very promising and potentially cost effective manufacturing process for complex structural composite parts. However, most of possible cost savings are currently not realized because of the great expense involved in hand layup of individual composite plies on three dimensional forms. We have begun to investigate double diaphragm forming as a possible means to readily produce 3D composite preforms from 2D ply stacks. These preforms could then be quickly and easily incorporated in an RTM mold, thus making RTM a much more cost effective manufacturing process.

To assist us in this investigation we have developed several techniques which provide quantitative data from which we can measure the quality of the preforms produced, and compare the relative effects of process and material variations. By manipulating this data one can calculate the fabric deformation and tow spreading that occurrs as a consequence of forming. The ability to see the distribution and magnitude of these phenomena has provided much insight into the important mechanisms involved in double diaphragm forming. These methods have also allowed us to validate and improve on a simulation of the draping of woven fabric over 3D forms.

Acknowledgments

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References

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