

Forming of Advanced Composite Materials

by

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Mechanical Engineering

ABSTRACT

Two significant aspects of advanced composite material forming are examined. First, the fiber deformation of aligned fiber composites formed to double curvature parts is analyzed. Aligned fiber composite lay-ups were formed over hemispherical tools and the fiber deformation was mapped. The data were intended to support the model which predicts trellising of composite fibers in double curvature. The data are, in general, too ambiguous to clearly support this model. Second, springback of woven fiber material-single curvature parts is investigated. A 90° bend was formed for varying laminate lay-ups at varying temperatures via a double diaphragm process. Principal objectives were to qualify the effects of varying lay-ups and temperatures on the net amount of springback observed. The data show that 0/90 woven lay-ups experience more springback than either ±45 degree or quasi-isotropic woven lay-ups, and that heating the laminates marginally decreases the springback experienced.

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1.0 INTRODUCTION

The lay-up and forming of advanced composite materials for useful parts is a time and cost intensive process. Aspects of composite forming examined in this thesis were motivated not only by the desire to increase the general knowledge base of composite material part designers and manufacturing engineers, but also by specific industrial application difficulties.

Two differing models, or expected patterns, of fiber deformation in aligned fiber composites experiencing double curvature motivated more investigation into this phenomenon. The “ideal shear” model assumes that the forming of a double curvature part is accommodated by in-plane fiber shear and interply shear. Preliminary experimental data showed that although the actual fiber mapping followed this pattern closely in some regions, in other regions it deviated from the expected pattern considerably. An alternative model suggests that double curvature is accommodated by a trellis type pattern of deformation between cross-plyed fibers. A more detailed description of each of these models will be provided later.

Experiments were conducted with Hercules aligned fiber material. A double diaphragm process was used to form laminates over hemispherical tools. Both laminate lay-ups and tool radii were varied. Fiber deformation was mapped after forming via a grid drawn on the laminate before forming.

A notable limitation encountered in the investigation of the fiber deformation of parts with double curvature was the high degree of difficulty in actually forming a hemispherical part successfully. Even moderately successful forming of parts required a fairly unregulated heating applied externally to the machine and diaphragms. In spite of

externally applied heating, wrinkling, a major failure mode for double curvature parts, was occasionally encountered. Wrinkling eliminated some of the data points from the fiber mapping of each part.

The investigation into springback of single curvature parts was motivated by the desire of The Boeing Co. to improve the forming process for a rib chord in the empennage, or tail structure, of the 777 model airplane. The particular part, called a rib chord, is essentially a curved L-bracket connecting horizontal ribs and vertical stringers; it improves the structural strength and rigidity of the tail structure. The part is made of a Hexcel woven composite material.

Again for these experiments a double diaphragm process was used in forming. Composite lay-ups were varied to investigate the differences in springback between 0/90 woven laminates and ± 45 on the bias lay-ups, as well as between each of those lay-ups and quasi-isotropic lay-ups. Temperature was also varied in each test to investigate the relationship between heating and amount of springback.

2.0 DOUBLE CURVATURE FIBER DEFORMATION

Fibers deformations were mapped for the double curvature parts. As previously stated, there are different mapping models for predicting the fiber deformation of aligned fiber composites, the type used in the double curvature experiments. One of the models suggests that the fibers will deform in an ideal shear manner. The other model, which is used extensively for woven composites, suggests that fiber deformations follow a different pattern of deformation referred to as trellising.

2.1 THEORETICAL BACKGROUND

Both models recognize that there are two significant shear deformation modes present. One is longitudinal in plane shear, in which fibers adjacent to each other in the same lamina slide relative to each other. The other is interply shear, in which whole lamina slide relative to each other. These models are described in more detail in the subsequent sections.

2.1.1 IDEAL SHEAR DOUBLE CURVATURE FIBER DEFORMATION MODEL

Consider a composite laminate consisting of two layers of aligned fiber composite. The bottom layer would be oriented at 0° , and the top layer would be oriented at 90° .

This model predicts that the fibers in each layer will shear in an ideal manner, and that interply shear will help to accommodate the double curvature. Restricted to these assumptions, all fibers would be parallel after forming. The figure on the following page shows what fibers in one layer would look like after being formed onto a hemispherical tool.

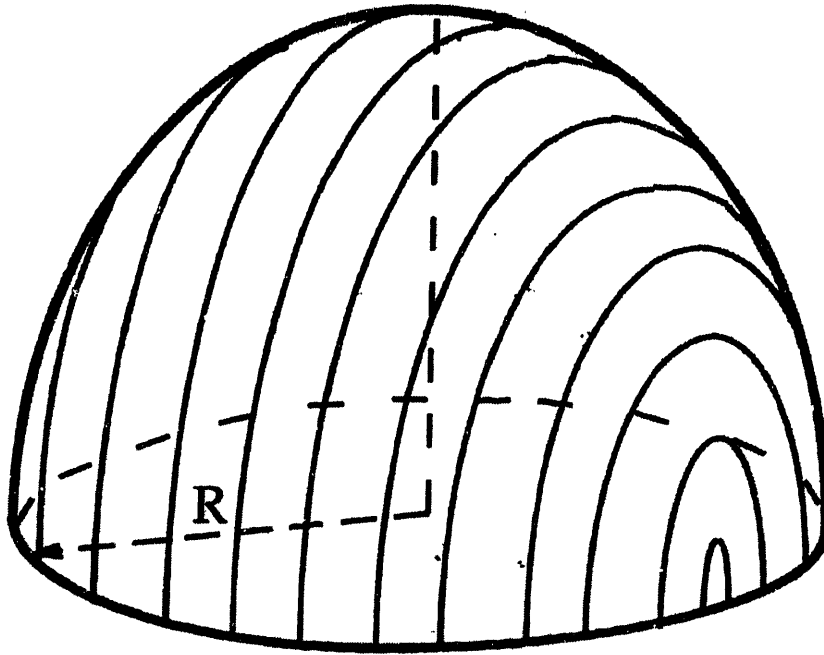


Figure 2.1 Parallel Fibers of a Deformed Aligned Fiber Composite - Ideal Shear Model. (Li, [1998])

Assume a point at coordinates x, y, z on each lamina prior to forming. This model can be used to calculate the final positions of each point after forming due to the interply shear necessary for the fiber deformation suggested by the model. It can be shown that the point on the on the bottom lamina will move to a new coordinate x_1, y_1, z_1 , and the point on the top laminate will also move to another location at coordinates x_2, y_2, z_2 . Further, the interply shear necessary to move each point from the original pre-forming coordinates to the final coordinates after forming can be calculated. The amount of interply shear is, in fact, quite high.

It has been observed in previous experiments by Li [1998] that the actual interply shear generally does not reach the magnitude required to correlate with this ideal shear model.

The fact that the observed interply shear is lower than the predicted interply shear is one discrepancy between this model and practical experience. Another discrepancy can be seen in the fiber mapping data. The fibers deform in a manner which correlates very accurately with the model from the top of the hemisphere until $\pi/4$, or halfway down the hemisphere. However, from $\pi/4$ to $\pi/2$, or the bottom of the formed laminate, the data deviate significantly from the ideal deformation model.

2.1.2 TRELLIS MODEL APPLIED TO ALIGNED FIBER COMPOSITES

The observed fiber deformation in double curvature parts does not follow the ideal model over the complete surface of the hemisphere. Considering the assumptions made by the ideal model, it is difficult to explain the deviation from the ideal model that fiber deformation showed in practice.

However, the trellising model for woven fabrics provided another possibility to predict the pattern of fiber deformation. The trellising model itself has been derived for woven fabrics for quite some time. It has also been applied to woven composites. However, Li [1998] has suggested that the trellising model may also be able to predict the fiber deformation pattern for aligned fiber composites.

Consider that in a woven material in its pre-formed state, fibers are interlaced with each other perpendicularly, with many fibers running along an x axis, and many fibers

running along a y axis. Ideally, the fibers in this condition are oriented so that they form rectangles with 90° angles, creating a large grid. Because the fibers are interlaced, their tendency to slide past one another is greatly diminished. Consequently the corners of the rectangles can be idealized as pin joints. During forming, tensile and compressive forces in each ply deform many of these grid rectangles into diamonds, forming a trellis-type pattern.

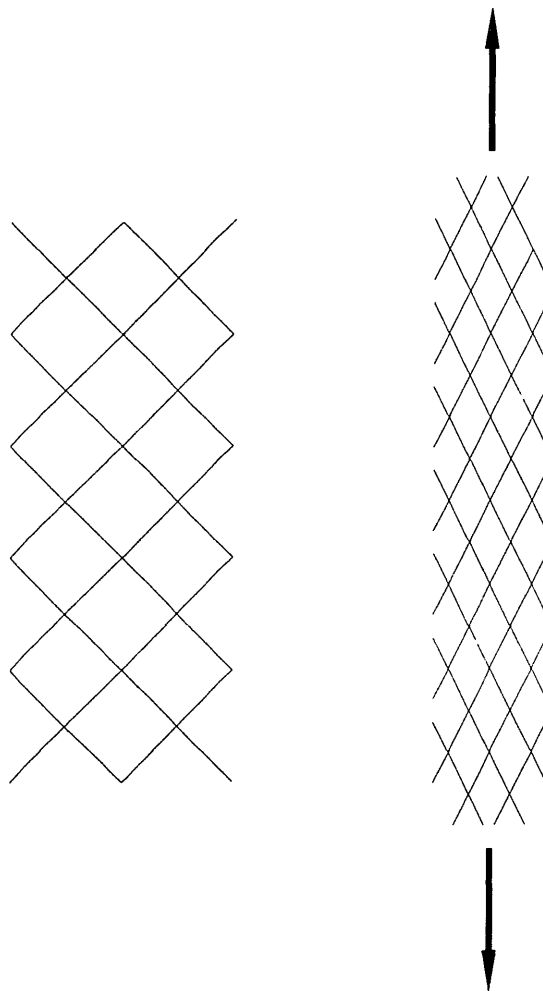


Figure 2.2 Composite Fibers in Undeformed State (left) and Showing Trellis Pattern (right) Under Tensile or Compressive Loads.

Under these assumptions, the fibers do not end up parallel to each other after forming onto a hemisphere as they do in the ideal shear model. Furthermore, area in a grid rectangle is not conserved, which results in a height change of the laminate. The following figure shows a section of lamina fibers in an undeformed state, and a section in the deformed state, according to the trellising model.

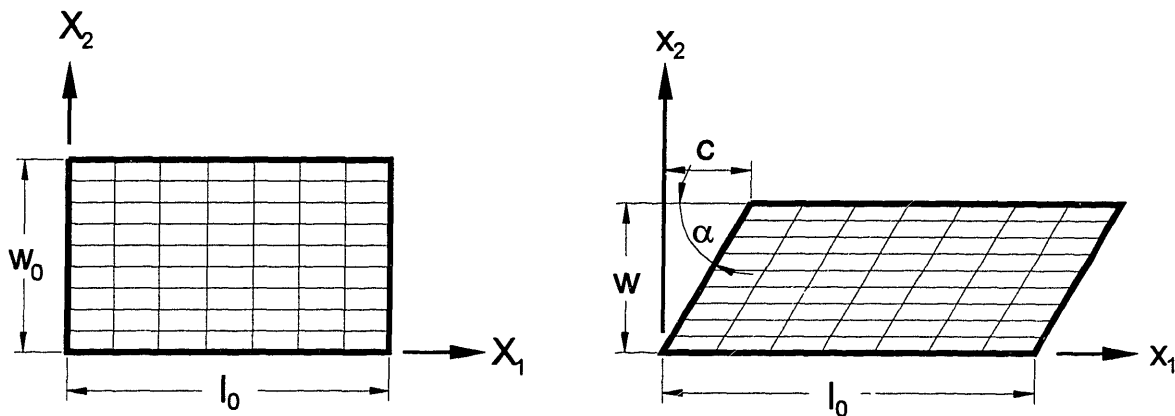


Figure 2.3 Undeformed Fiber Section (left) and Trellised Deformed Fiber Section (right). (Gutowski, et al [1997])

The ideal shear model states that the w would equal w_0 for the deformed section in the above figure. Area of the section is thus conserved, and lamina thickness does not change.

Li [1998] observed that experimental data for hemisphere forming follows this trellising model much more accurately than the ideal shear model. The data do not exactly fit the mathematically predicted trellising angles. That can not be expected because the actual deformation phenomena are more complex, including interply and longitudinal shear, for instance, in addition to trellising. However, the data follow a trend which is strikingly similar to the trellising model and very convincing in its support of that model.

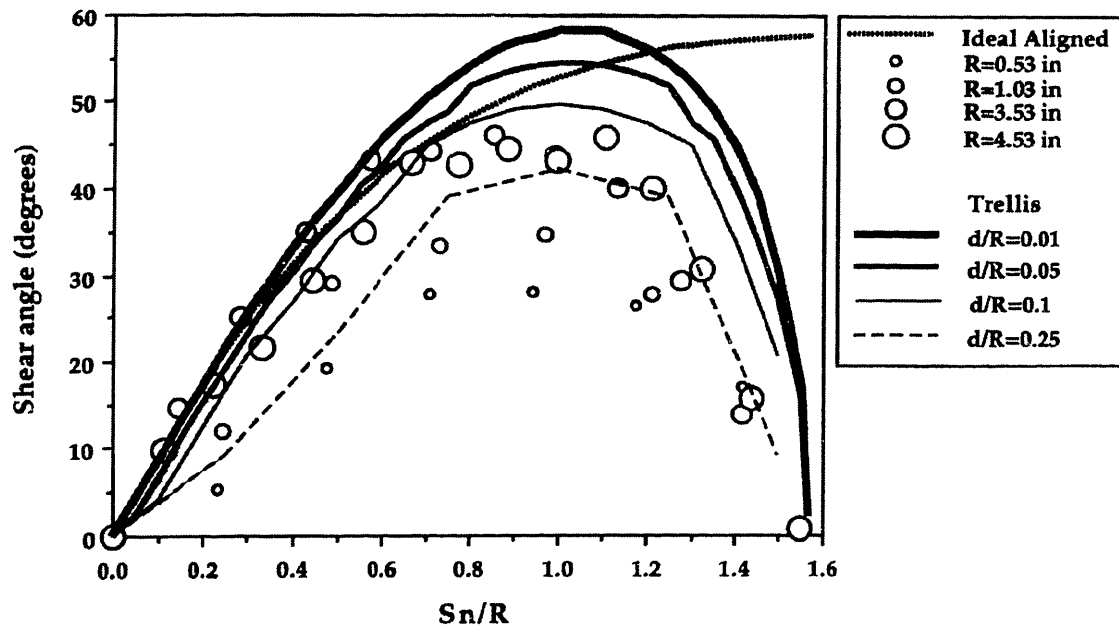


Figure 2.4 Normalized Experimental Hemispherical Part Data With Ideal and Trellis Model Predictions. (Li [1998])

2.2 DOUBLE CURVATURE HEMISPHERE FORMING PROCEDURE

A series of experiments were run in which composite laminates were formed over hemispherical tools using a double diaphragm process. Tests of varying composite lay-ups and hemispherical tool radii were conducted. The following table enumerates the experiments which were conducted:

| | | |
|---|--------------|------|
| 1 | [0/90/0/90] | 2.55 |
| 2 | [0/90/90/90] | 2.55 |
| 3 | [0/90/0/90] | 3.66 |
| 4 | [0/90/90/90] | 3.66 |
| 5 | [0/90/90/90] | 3.66 |

Table 2.1 Double Curvature Hemisphere Forming Experiments.

*All sample are 4 plies thick.

2.2.1 COMPOSITE DESCRIPTION & SAMPLE PREPARATION

The composite material used in the double curvature hemisphere experiments is an aligned fiber material manufactured by Hercules. The material designation is AS4/3501-6.

Twelve inch pieces were cut from a twelve inch wide roll of the material. These lamina were laid up in various orientations depending on the particular experiment. Laid

up laminates were cut using a template to give a shape which would result in a hemisphere. The template shape is based on the theoretical deformation of aligned fiber laminates as given by the ideal model discussed in section 2.1.1.

After the laminates were prepared, a grid with 0.5 inch squares was drawn on each laminate with a white colored pencil. The grid allowed a fiber mapping to be done after forming by observing the deformation of the grid.

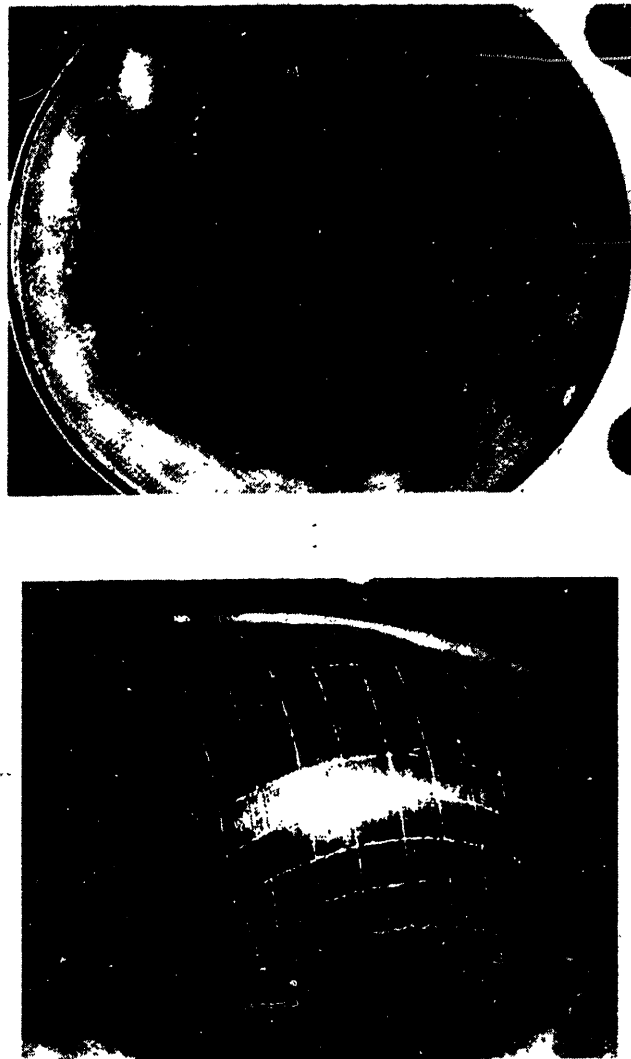


Figure 2.5 Grid Drawn Pre-Forming (top) and After Forming (bottom). (Li [1998])

2.2.2 EXPERIMENT PROCEDURE

The double curvature experiments were performed using a double diaphragm procedure. Silicone was sprayed on each diaphragm to allow the laminate to slide past the diaphragms. Additionally, a layer of fabric was inserted between each laminate/diaphragm interface to reduce the friction between them.

First, the bottom diaphragm was put on the machine. Next the laminate was centered on the tool. Then a thermocouple and an air tube were positioned on the bottom diaphragm near the laminate. Lastly, the top diaphragm was lowered onto the machine and bolted down, securing the laminate and thermocouple between the sealed diaphragms.

The thermocouple was used to obtain a rough measurement of laminate temperature during the experiment. Due to the difficulties of forming aligned fiber hemispheres, the parts were heated throughout the course of the forming in order to obtain a higher quality part. Heating was done with a heat gun external to the machine. Measured temperature ranged from 95 to 125 °F during forming.

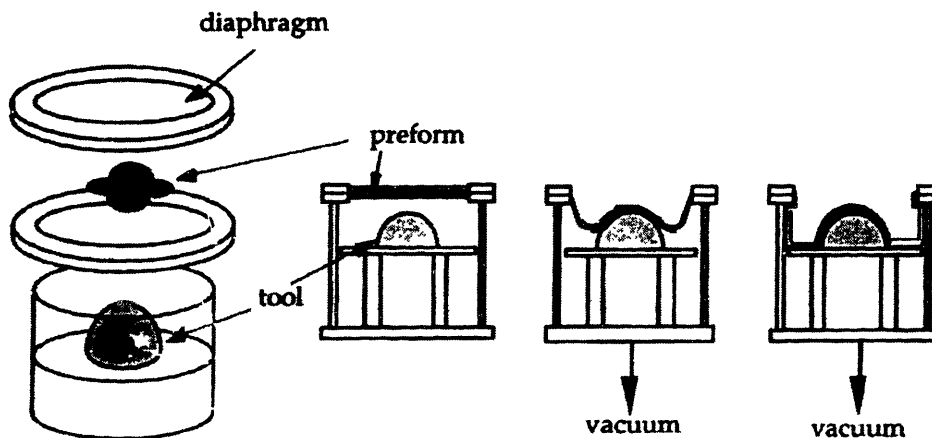


Figure 2.6 Schematic of Double Diaphragm Forming Process. (Gutoswki, et al [1995])

After an initial heating, a vacuum was drawn between the diaphragms using the air tube which was inserted. Then the vacuum in the chamber was initiated. This vacuum needed to be drawn very slowly in order to achieve parts which were not severely wrinkled. Forming time was generally on the order of 45 to 60 minutes.

2.2.3 MEASUREMENT PROCEDURE

A grid was drawn on the undeformed flat laminate, then deformation measurements were taken on the fully formed laminate. All parts were formed on hemispherical tools. The grid was oriented such that two perpendicular lines intersected in the center of the laminate. Each of these rows was designated as Row 0, either in the Fiber direction (parallel to the fibers), or in the Non-Fiber direction (perpendicular to the fibers). Going outward toward the bottom edge of the hemisphere, rows were numbered arbitrarily positively in one direction, and negatively in the other direction.

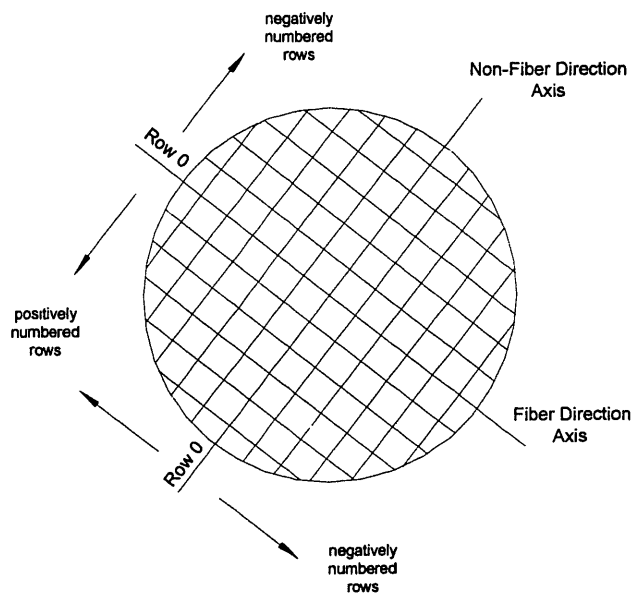


Figure 2.7 Grid Marking and Numbering System.

The deformation angles were measured row by row. Starting with Row 0 in the Fiber direction, the new grid angles were measured in one direction from the highest numbered positive row (depending on tool/laminate size) to lowest numbered negative row. That process was repeated for all grid lines in the Fiber direction. In this manner, the complete grid was mapped and the same angle was measured in each grid square. Some data was lost due to laminate wrinkling or grid markings which became unreadable after the forming process. The following figure describes the angle, σ , which was measured from the tangents at the fiber intersection points.

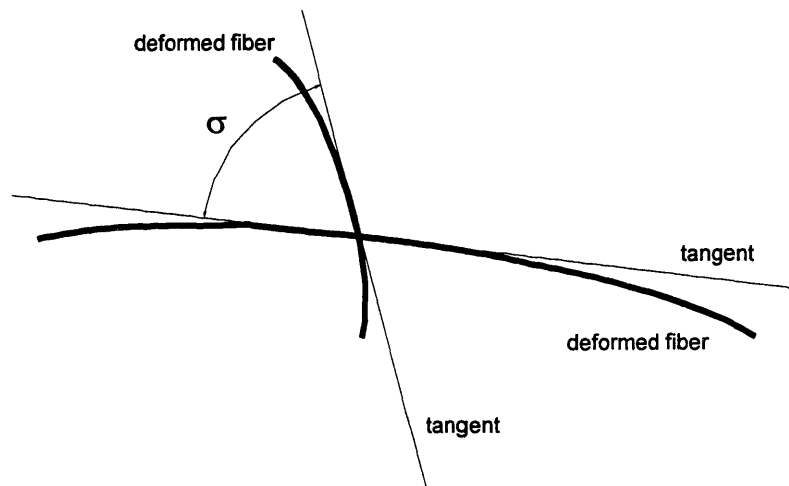


Figure 2.8 Measurement Angle Sigma Used to Describe Fiber Pattern After Forming.

2.3 DOUBLE CURVATURE HEMISPHERE FORMING RESULTS

Complete fiber mappings were recorded for a half inch grid on all experimental samples. The data were interpreted by graphing the shear angles for one quadrant on a 3-D surface. The shear angle graphed is defined by:

$$90 - \sigma = \alpha \quad \text{Eq. 2.1}$$

where σ is the deformed grid angle which was recorded during measuring and α is the angle which was graphed.

The following figure shows the 3-D surface graph for a deformed composite quadrant with shear angles calculated by the trellising model:

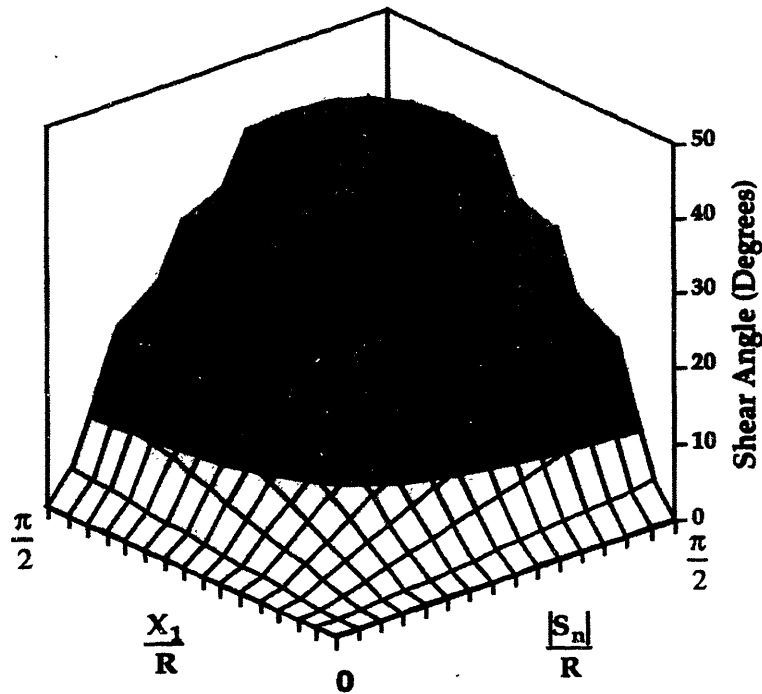


Figure 2.9 One Quadrant of Trellising Model Predicted Shear Angles, where $d/R=0.1$. (Li [1998])

The graph shows that the shear angles are symmetric about the diagonal through the quadrant, which is an important characteristic of the trellising model. The shear angles in the trellising model, unlike in the ideal shear model, are dependent on the fiber grid size and the overall laminate size. These factors are characterized by the ratio:

$$d/R \qquad \qquad \qquad \text{Eq. 2.2}$$

Where d is the characteristic length of the grid size and R is the radius of the laminate.

The graph on the following shows the results for a quadrant of the laminate formed in Test 3; a [0/90] lay-up formed over a 3.66 inch tool. The precise d/R ratio is unknown. Li [1998] found that a particular value for d is difficult to pinpoint for aligned fiber composites. For instance, a particular value for d may correlate the fiber trellising model well with experimental data from a test which used a certain tool radius. However, that same value for d would not correlate the fiber trellising model with experimental data from a test which used a tool with a different radius. For woven fiber structures, d is related to the nature of the weave.

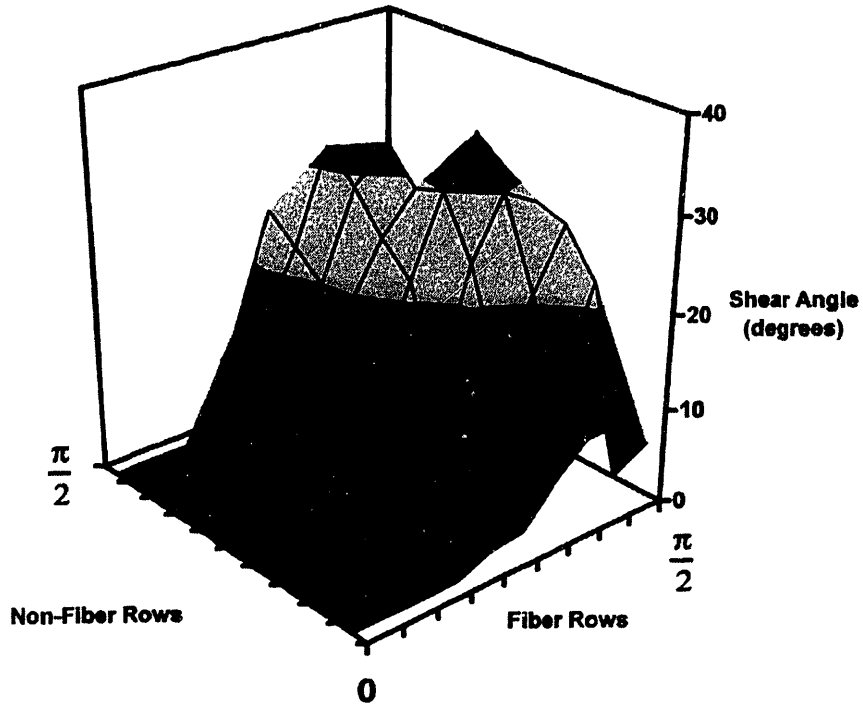


Figure 2.10 Shear Angles for Experiment 3.

The data from this quadrant shows that the experimental shear angles are nearly symmetric about the diagonal through the quadrant. The shear angles are also low near the top of the hemisphere increasing to maximum values near the edge of the deformed laminate as expected. The actual magnitude of shear angles is smaller by about 20% than that predicted by the model. Though the experimental data do not exactly match the theoretical data, the general trend of the trellising model is supported by the experimental

data. Referring to Figure 2.4, it can be seen that by increasing the d/R ratio, the trellising model can predict shear angles which are closer to those found in Experiment 3. However, increasing the d/R ratio too much will lead to unrealistic fiber grid sizes.

The other experiments did not clearly support either the ideal shear model or the trellising model. The following graph shows the data from Experiment 4.

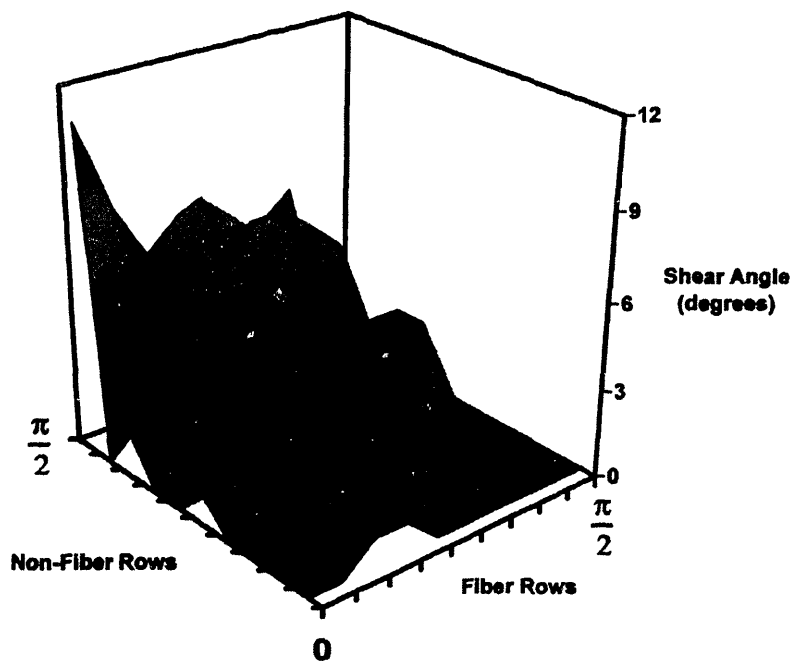


Figure 2.11 Shear Angles for Experiment 4.

One characteristic that can be clearly seen in this graph is that the shear angles are not symmetric about 45° , or the diagonal through the quadrant. Shear angles of higher magnitude tend to be shifted toward one edge of the quadrant, as they are in the ideal shear

model. The magnitude of all shear angles, though, is much less than that predicted by either model. The ambiguous nature of this data makes it difficult to draw solid conclusions. But it appears that other deformation mechanisms are available which allow the laminate to form into the shape of a hemisphere without either ideal shear or trellising. The most likely other mechanisms are spreading and bunching of fibers. Both of these are related to the transverse shear properties of the fiber bundles.

Data from experiments 1, 2, and 5 also showed shear angles of a smaller magnitude than expected. All five experiments for which data is given resulted in fairly well-formed hemispheres. (Some experiments were run in which wrinkling was so extensive that measurements were not taken.) No perfect hemispheres were formed, though, and in each case approximately 2% of the data points were lost due to wrinkling. For the data from experiments 1, 2, and 5, please see Appendix A.

3.0 FORMED LAMINATE SPRINGBACK

Currently, the rib chord in the empennage of the Boeing 777 is made of woven composite prepregs which are laid up by hand. Because the part is laid up on the tool by hand, springback is not an issue. Serious drawbacks of hand lay-up, though, are time and cost. In order to increase the efficiency and flexibility of the rib chord manufacturing, MIT graduate student Sam Truslow is attempting to optimize a double diaphragm forming process for the rib chord. Consequently, because double diaphragm formed parts start flat between two diaphragms and are then deformed to the tool, springback of the parts becomes a significant issue.

3.1 THEORETICAL BACKGROUND

Bending of an uncured composite beam can exhibit a variety of deformation behaviors. It is known from experience that there are several phenomena occurring simultaneously in the deformation of composites. This is due largely to the fact that they are composites, one material comprised of different materials with different material properties. The material properties of the solid fibers, for instance, are much different from those of the viscous resin.

Deformation modes occurring in the springback experiments include simple, or pure, bending, assuming there is no shear force transmitted by the diaphragms to the samples. This situation might be modeled with the laminate as a beam, its cross-sectional area equal to the width of the laminate times its height (the total height of the laminate).

However it might also be modeled as the sum of several beams, with each lamina being a beam with cross-sectional area equal to the width of the laminate times the height of a lamina. This mode is interply shear. Each laminate sample is made up of several layers, and no layers are completely fixed to each other. Therefore, rather than the top layer undergoing an extreme amount of tension or the bottom layer experiencing extreme compression, each lamina slides relative to the others during bending.

In addition to interply shear, there is limited longitudinal shear, or slippage between fibers. Slippage can occur as viscous slip, which is highly rate and temperature dependent, or as frictional slip, which has only limited dependence on rate and temperature.

Trellising is yet another deformation mode. This probably occurs to a significantly higher degree in some of the springback experiment lay-ups due to initial fiber orientation

in the samples. This fact further complicates construction of a model that applies to all samples.

These are all possible deformation modes, and probably do not even include all physical phenomena occurring in the experiments. No satisfactory model currently exists that can encompass all of the observed deformation modes. (Li [1998])

3.2 SPRINGBACK PROCEDURE

A series of experiments were run in which woven composite laminates were formed using a double diaphragm process over rectangular tools. Tests of varying composite lay-ups were run with several samples at different temperatures. The following table enumerates the experiments which were conducted.

| | | | |
|---|---------------------------|----|----------------------|
| 1 | 0/90 vs. +/-45 | 8 | room (~69), 125, 140 |
| 2 | 0/90 vs. +/-45 | 16 | " |
| 3 | 0/90 vs. +/-45 | 24 | " |
| 4 | 0/90 vs. quasi-isotropic | 10 | " |
| 5 | 0/90 vs. quasi-isotropic | 18 | " |
| 6 | +/-45 vs. quasi-isotropic | 10 | " |
| 7 | +/-45 vs. quasi-isotropic | 18 | " |

Table 3.1 Springback Experiments.

The tests were designed to examine the significance of both thickness (number of plies) and temperature for varying lay-ups. The 18 ply quasi-isotropic laminates are of the orientation of the rib chord in the Boeing 777.

3.2.1 COMPOSITE DESCRIPTION & SAMPLE PREPARATION

The composite material used in the springback experiments is a woven material from Hexcel. The material designation is W3T 282 with a F593-18 resin system. It is the material with which The Boeing Co. makes the rib chord for the 777.

Strips of composite were cut from a roll in 4 inch wide segments, either at 45° or 90° to the roll. Lamina were then cut from both the 45° and 90° strips in 2 inch pieces. The individual pieces were laid up depending on orientation and number of plies required for each test.

3.2.2 DETERMINATION OF SAMPLE LENGTH

The dimension of the samples which was perpendicular to the tool remained constant at 4 inches. In order to initially determine if the length of a part - that is, the dimension parallel to the tool - would be a factor in the amount of springback, samples of 2" and 8" lengths were simultaneously formed under identical conditions. The similarity in net springback of the samples of different length indicated that length would not be a significant factor in the amount of springback. It was determined that 2 inch samples

would be used for further experiments to conserve material. The following figure describes the difference in initial sample sizes.

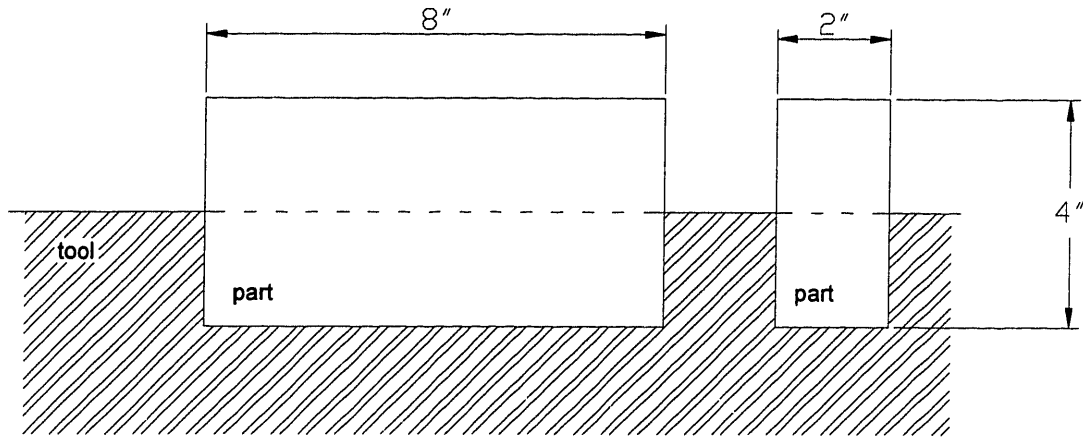


Figure 3.1 Eight Inch vs. Two Inch Initial Sample Sizes (Top View).

3.2.3 TEST PROCEDURE

Six samples in three sets of two samples each were run in each springback test.. In order to determine the effect of temperature on springback, samples in each of the three sets were exposed to different temperatures. Consequently, one set had a sample of each lay-up at room temperature, one set had a sample of each lay-up at 125°F, and one set had a sample of each lay-up at 140°F. The heated sample temperatures were allowed to vary within plus or minus 1°F.

Samples were heated using an air supply, a heating element system built by Sam Truslow, and plastic coolers. One cooler had the 125° samples and another had the 140° samples. The curing reaction of this particular composite begins at 150°. Consequently,

Boeing requested that 140° be the upper temperature limit. Air hoses supplied air to each cooler. Temperature was regulated by controlling air flow into the coolers. Both valves for each air hose and a valve which regulated pressure of the air source were used to control the air flow.

One thermocouple was fixed at the outlet of each air hose to measure the temperature of the air flow into the coolers. Because the temperature of air flow going into the high temperature cooler was over the limit of 140°, and sometimes near the 150° at which the curing reaction starts, small baffles were attached at the end of each air hose. The implementation of these baffles ensured that the composite samples would not be heated by the direct stream of air coming into the cooler, but rather by convection currents. The following figures describe the baffle which was attached to the end of the air hoses (Figure 3.2), and the arrangement of the hose and baffle in the coolers (Figure 3.3).

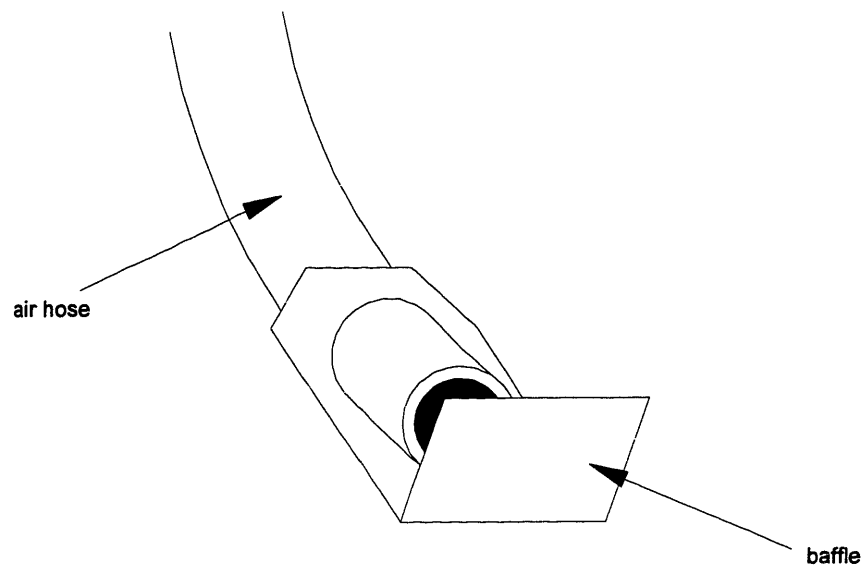


Figure 3.2 Air Hose Baffle.

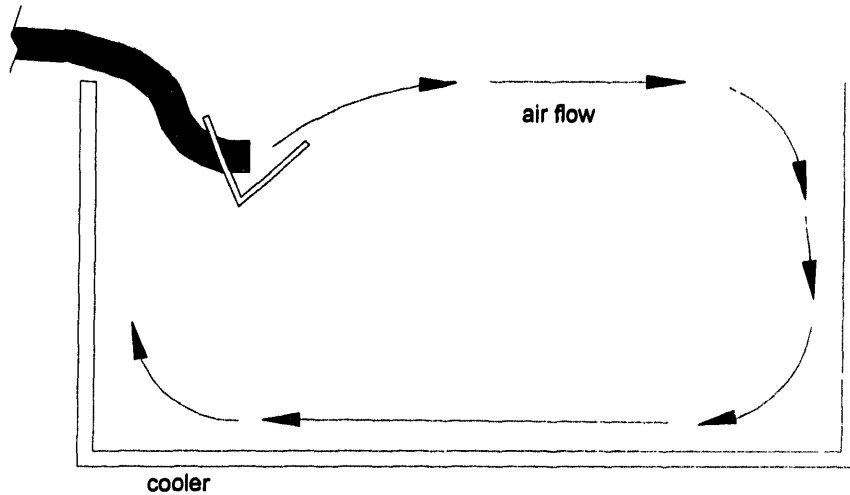


Figure 3.3 Air Flow in Composite Sample Heating Coolers.

Another thermocouple was inserted into each cooler to measure the ambient air temperature, the temperature assumed to be that of the sample. Samples of 10 or less prepreg layers were heated between 10 and 15 minutes. Samples of 16 or more prepreg layers were heated between 20 and 25 minutes.

Each sample was marked with test number, number of plies, lay-up, and temperature. Once sample heating was completed, samples were taken out of the coolers and taped on the lower diaphragm which rests against the forming tool. The diaphragm and tool were at room temperature. Samples cooled for approximately 1-2 minutes between being removed from the coolers and the beginning of forming. All samples were oriented perpendicular to the tool, with 2 inches of material on the tool and 2 inches

overhanging. A fabric was placed over the samples to allow the diaphragms to slide past the composites better.

The upper diaphragm was lowered onto the tool, and the frame holding the upper diaphragm was sealed with steel pipes applied across it. Then the air tube from one vacuum pump was attached to the valve in the top diaphragm. Immediately that vacuum pump was turned on to evacuate the air between the diaphragms, forcing them together. Once that vacuum was successfully formed, the second vacuum pump was turned on, evacuating the chamber in the forming machine underneath the bottom diaphragm. The evacuation of the chamber naturally caused both diaphragms to be forced downward onto the tool and machine due to the pressure differential.

Because the springback samples were only deformed with a single curvature, they could be formed much faster than the hemispheres. Forming time was on the order of 5 minutes for all experiments. Once the parts were sufficiently formed by drawing down the diaphragms, both vacuum pumps were turned off. Air was then evacuated from between the diaphragms, allowing the top diaphragm and frame to be raised. The raising of the top diaphragm allowed access to the formed samples.

After the top diaphragm was raised, the fabric was removed from the samples. There was slight sticking of the fabric to the samples, but it did not result in substantial extraneous deformation. Once the fabric was removed, samples were immediately marked at the tool line, taken off the bottom diaphragm, and transferred to another aluminum tool for measuring. The mark at the tool line was used to properly seat the sample on the aluminum measurement tool.

3.2.4 MEASUREMENT PROCEDURE

Measurements of the springback amount started 5 minutes after forming, defined in this case as 5 minutes after the samples were removed from the bottom diaphragm of the forming machine. More measurements were taken at 5 minute intervals until 30 minutes after forming. Then measurements were taken at approximately 2, 4, 8, 24, and 28 hours after forming.

A line was scribed on the vertical face of the aluminum measuring tool at 32 millimeters. The horizontal distance between the vertical face of the measuring tool and the composite sample was recorded in millimeters at each measuring time. Those distances, the measured horizontal distance and the vertical distance of 32 mm, were used to calculate the springback angle. The springback angle was defined as the angle between the vertical face of the measuring tool and the composite sample. The following figure describes the springback angle.

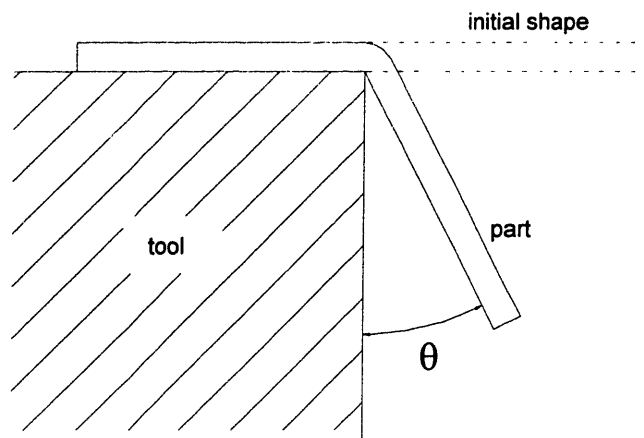


Figure 3.4 Measured Springback Angle, Theta.

3.3 SPRINGBACK EXPERIMENT RESULTS

Springback experiment results were graphed as springback over time. The following subsections include the results for the 0/90 vs. ± 45 comparisons, the 0/90 vs. quasi-isotropic comparisons, and the ± 45 vs. quasi-isotropic comparisons.

3.3.1 EXPERIMENTAL RESULTS OF 0/90 VS. ± 45

Referring to Table 3.1, three experiments were run to compare the springback of a 0/90 woven lay-up and a ± 45 woven lay-up. Part thickness was varied by varying the number of plies to determine its effect on the springback. The following graph shows the results for the 8 ply samples:

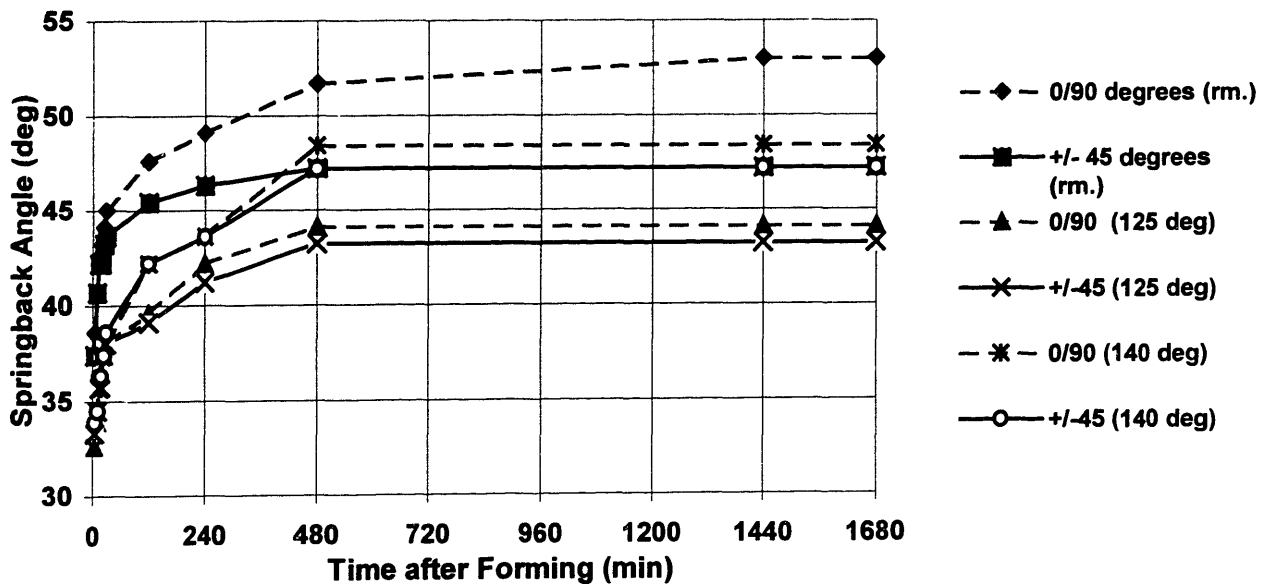


Figure 3.5 Results of 8 Ply 0/90 vs. ± 45 Lay-ups Springback Experiments.

Several trends can be discerned from the graph. The first shows that the 0/90 lay-ups experience more springback than the ± 45 lay-ups. The second trend shows that a lot of springback occurs in the 2 hours after forming, but that the springback effects generally level off after 8 hours. The third shows that heating does tend to diminish the amount of springback. However, interestingly, the springback in the samples heated to 140° was for the most part greater than that experienced by the samples which were heated to 125° .

The graphs for the 16 and 24 ply experiments are similar. The springback levels off a little more slowly in the thicker plies. Also, the overall magnitude of the springback is marginally less. Again, the difference between the 125° and 140° samples is slight, with the 140° samples at some points experiencing more springback than the 125° samples. For those graphs, please see appendix B. The following graph shows the relationship between sample thickness and springback by comparing the 8, 16, and 24 ply samples which were heated to 125° .

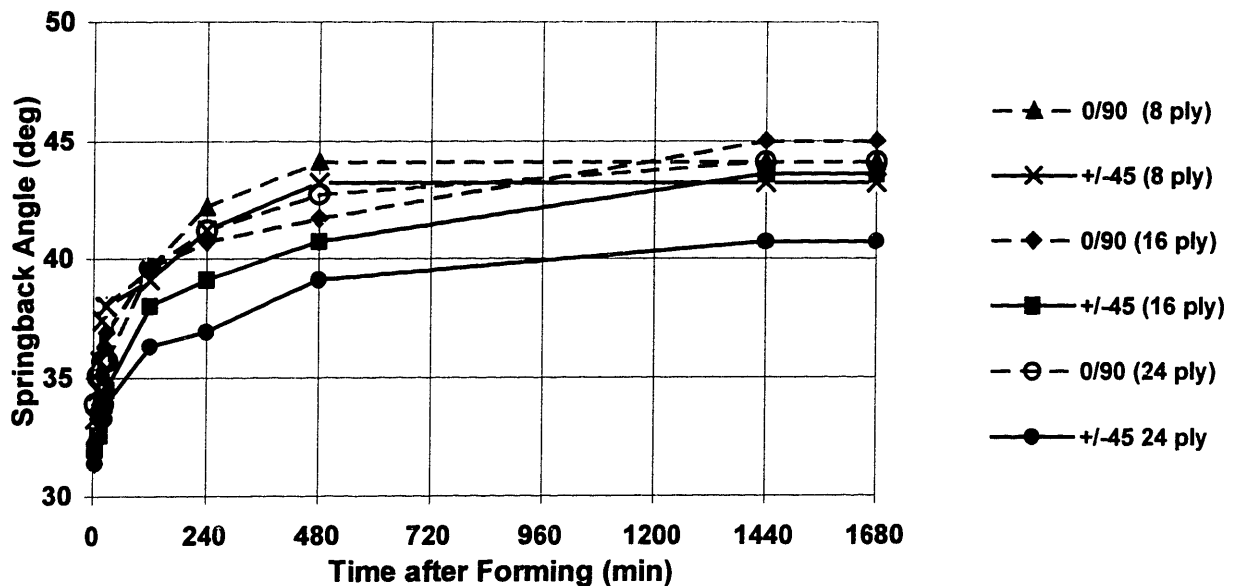


Figure 3.6 Sample Thickness Comparison for 125° Samples.

3.3.2 EXPERIMENTAL RESULTS OF 0/90 VS. QUASI-ISOTROPIC

The following graph shows the results for the 18 ply samples comparing a 0/90 lay-up with a quasi-isotropic lay-up (Figure 3.6). The 18 ply quasi-isotropic lay-up is the lay-up used by Boeing for the 777 rib chord and will not be described here due to proprietary concerns. Also shown on the next page is a blown-up graph of the region from 0 to 120 minutes after forming (Figure 3.7).

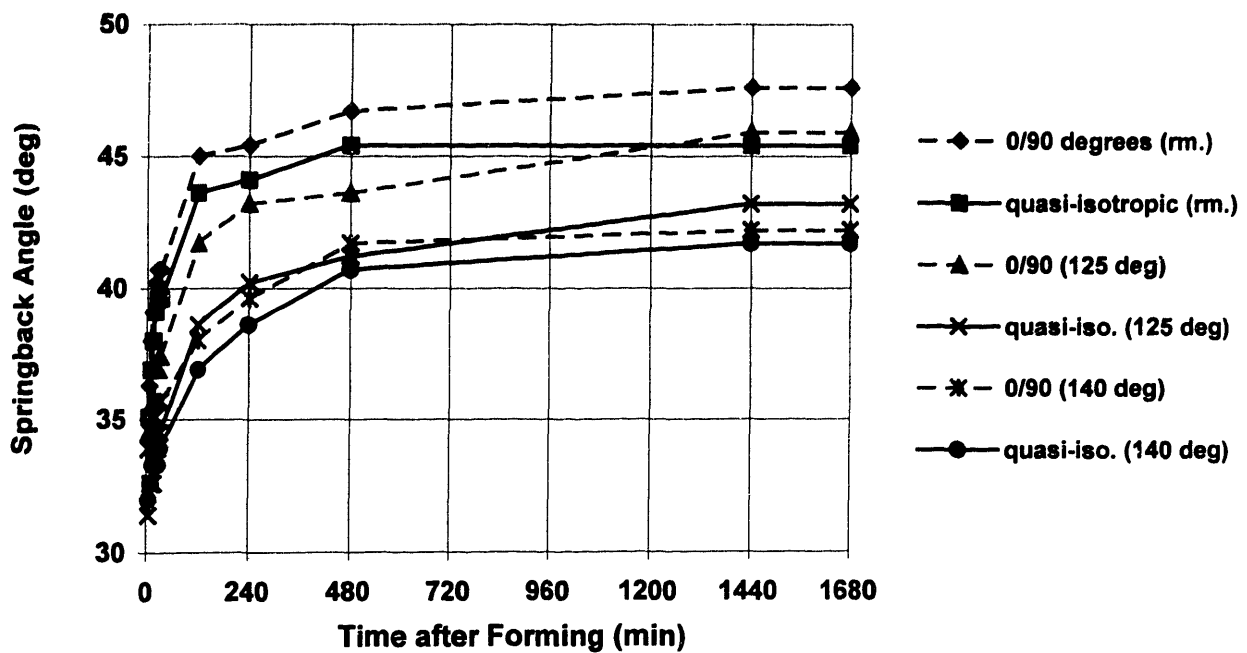


Figure 3.7 Results of 18 Ply 0/90 vs. Quasi-isotropic Lay-ups Springback Experiments.

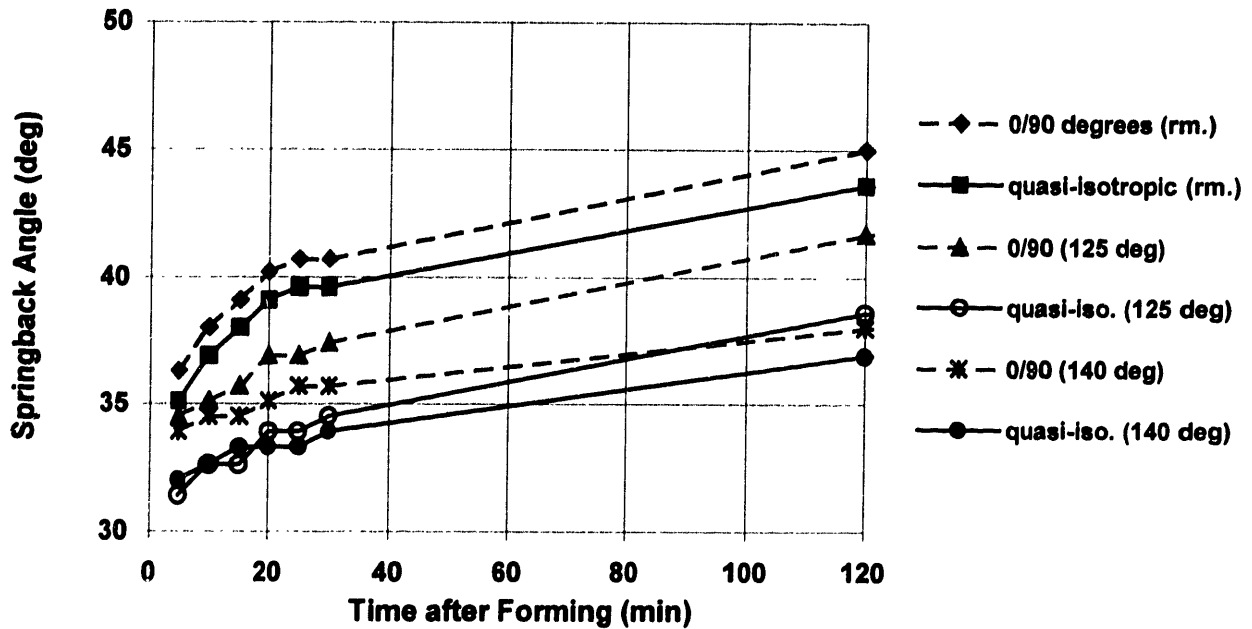


Figure 3.8 Same Results from 3.7 - Blown-up Region from 0 to 120 Minutes.

Several similar trends are found on these graphs that are found in the 0/90 vs. ± 45 graphs. The 0/90 samples generally spring back more than the quasi-isotropic samples. Springback levels off after 8 hours. Heating tends to diminish the amount of springback, but 140° is not necessarily much improved over 125° . For the graph of the 10 ply samples, please see Appendix C. The graph on the next page shows the relationship between sample thickness and springback for those samples heated to 125° .

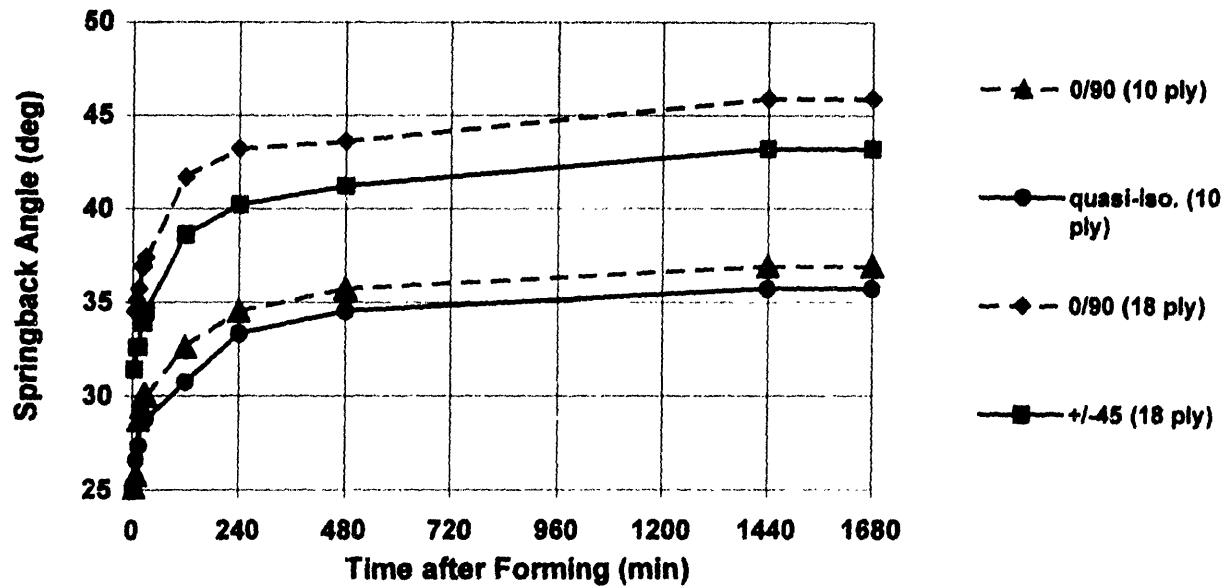


Figure 3.9 Sample Thickness Comparison for 125° Samples.

3.3.3 EXPERIMENTAL RESULTS OF ±45 VS. QUASI-ISOTROPIC

The graph on the following page shows the results for the 18 ply samples comparing a ±45 lay-up with a quasi-isotropic lay-up. The 18 ply quasi-isotropic lay-up is again the lay-up used by Boeing for the 777 rib chord. A blown-up graph of the region from 0 to 120 minutes can also be found on the following page.

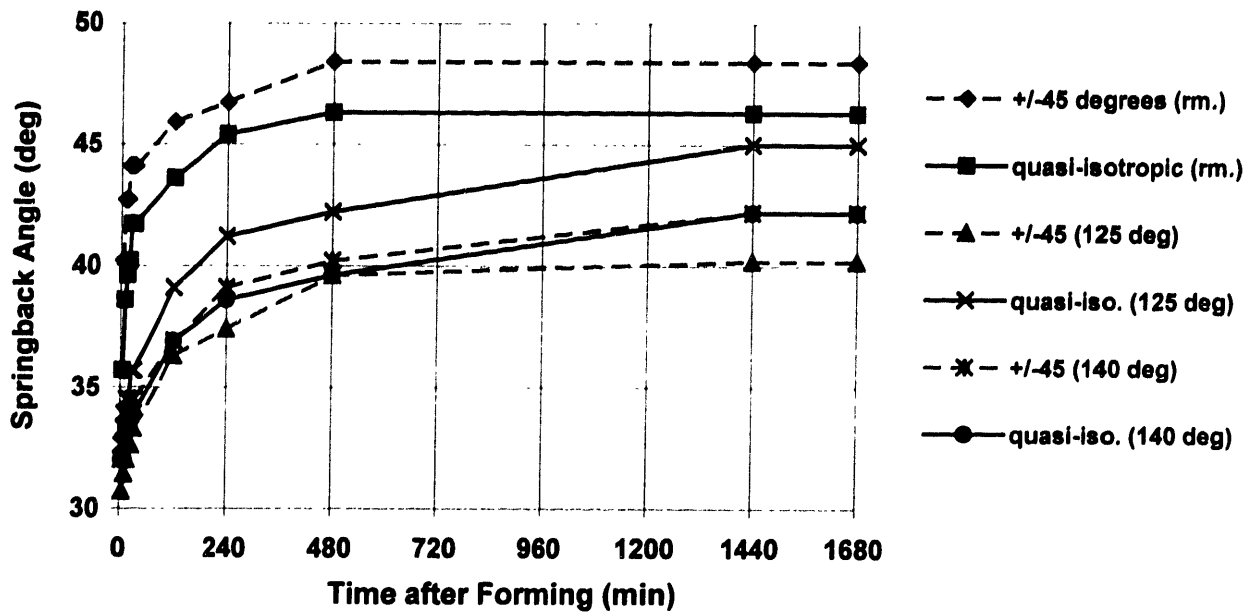


Figure 3.10 Results of 18 Ply ± 45 vs. Quasi-isotropic Lay-ups Springback Experiments.

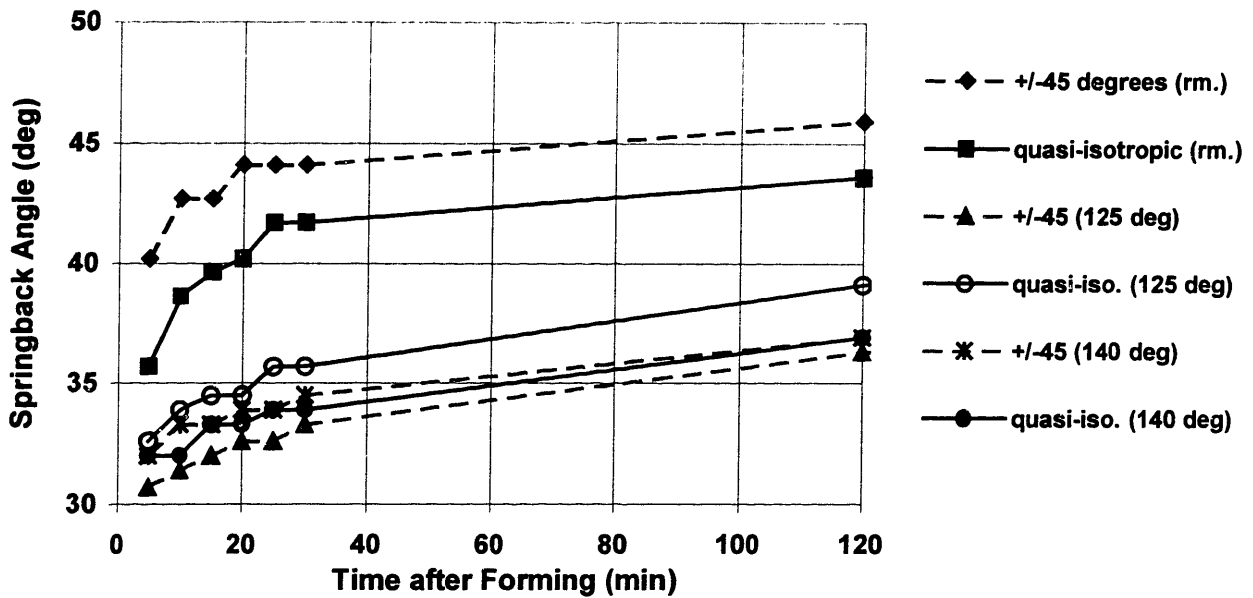


Figure 3.11 Same Results from 3.10 – Blown-up Region from 0 to 120 Minutes.

Trends seen in this graph are similar to those of all other graphs. The behavior vs. time and due to heating are similar to all other experiments. The behavior of ± 45 lay-ups as compared to the quasi-isotropic lay-ups is ambiguous, though, with one temperature experiencing more springback in the ± 45 lay-up, one temperature roughly the same, and one temperature experiencing less springback than the quasi-isotropic sample. For the 10 ply results, please see Appendix D.

The following graph shows the relationship of sample thickness to springback by comparing the 10 and 18 ply sample which were heated to 125° .

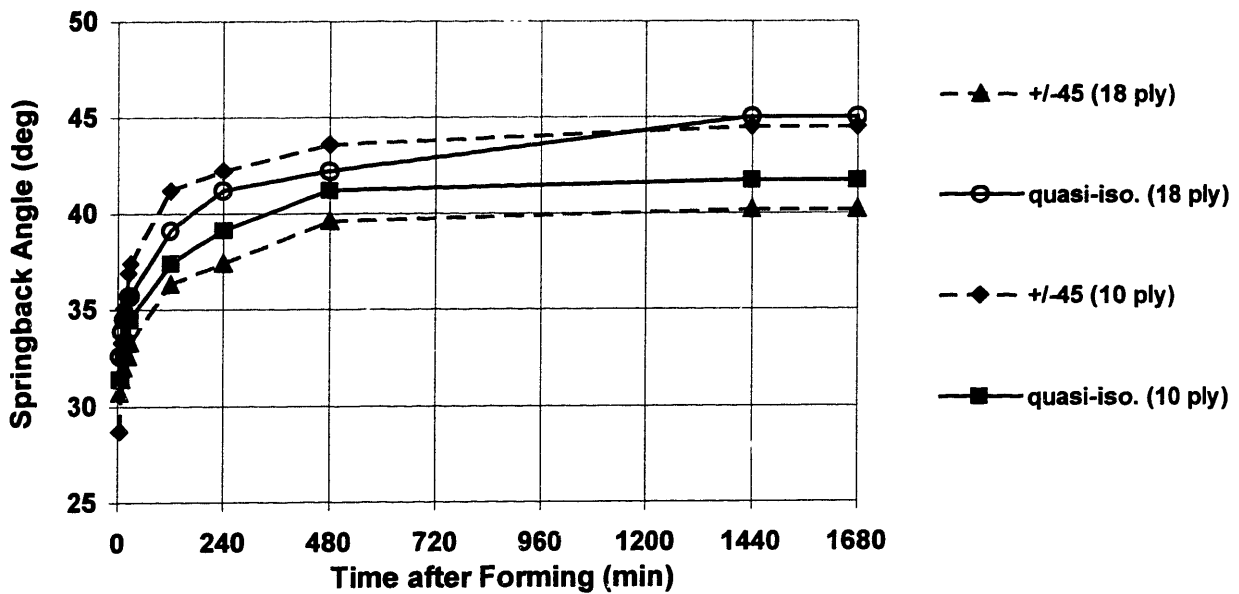


Figure 3.12 Sample Thickness Comparison for 125° Samples.

4.0 CONCLUSION

The data from the double curvature hemisphere forming experiments are intended to aid part designers and manufacturing process designers predict fiber deformation in order to improve both part design for specific parameters and process design with regard to known part forming failure modes. Additionally, there are many composite deformation CAD models which are also attempting to aid designers. Models which are based on fiber mapping should be based on the correct assumptions, whether it be an ideal shear model, trellising model, or some combination of models, to be as effective as possible.

Because the data from the experiments presented here is inconclusive, and perhaps even suggests that deformation modes like fiber spreading and bunching may be more important than previously considered, more experiments should be done. If possible, parts of different sizes, particularly larger parts, should be formed. Unfortunately, the larger the hemisphere, the more difficult successful forming is.

This double curvature information and these CAD models will become even more important as more attempts are made to incorporate double curvature parts into industrial applications. The first double curvature part in production is the rib chord of the Boeing 777. Because of the complexity of forming a double curvature part, the rib chord is currently laid up by hand.

Substituting a double diaphragm or other automated forming process for hand lay-up to manufacture these parts will be more efficient and therefore more cost-effective. If the double diaphragm process is used, though, springback of parts becomes a major issue. The data from the springback experiments are intended to facilitate this process change.

It should be noted that the springback is always at least near 25° , and almost reached 55° in one experiment. That is quite substantial part deformation which will need to be addressed. Many parameters in a double diaphragm forming process for the rib chord will have to be optimized. The experimental data from the springback experiments should help to optimize some of those parameters.

APPENDIX A

**DOUBLE CURVATURE HEMISPHERE
FORMING DATA**

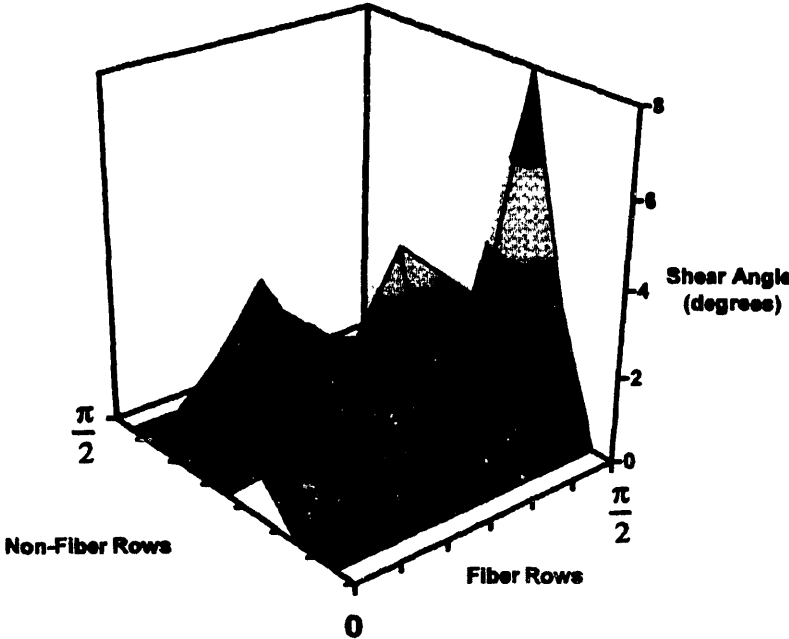


Figure A.1 Shear Angles for Experiment 1.

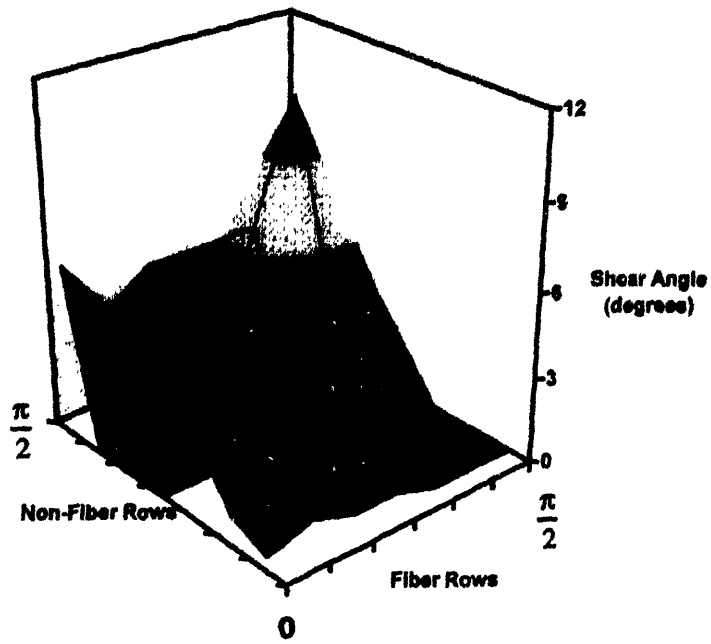


Figure A.2 Shear Angles for Experiment 2.

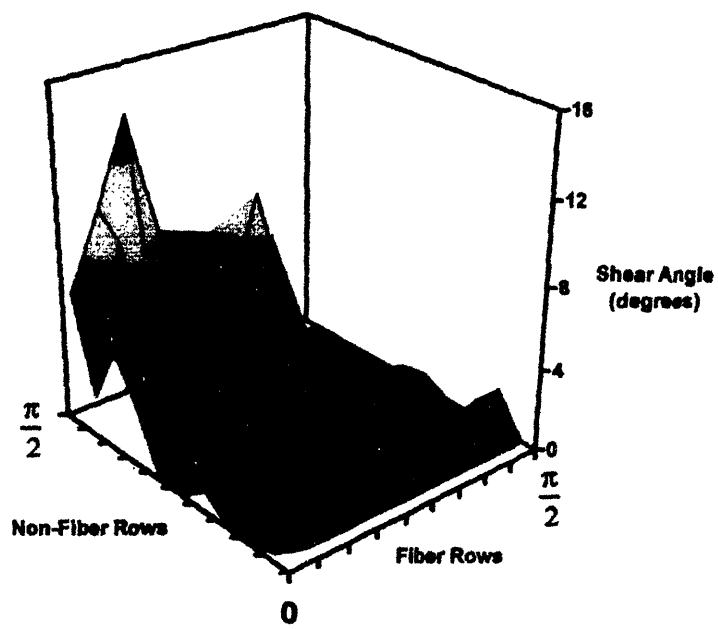


Figure A.3 Shear Angles for Experiment 5.

APPENDIX B

**RESULTS OF 16 AND 24 PLY
SPRINGBACK EXPERIMENTS**

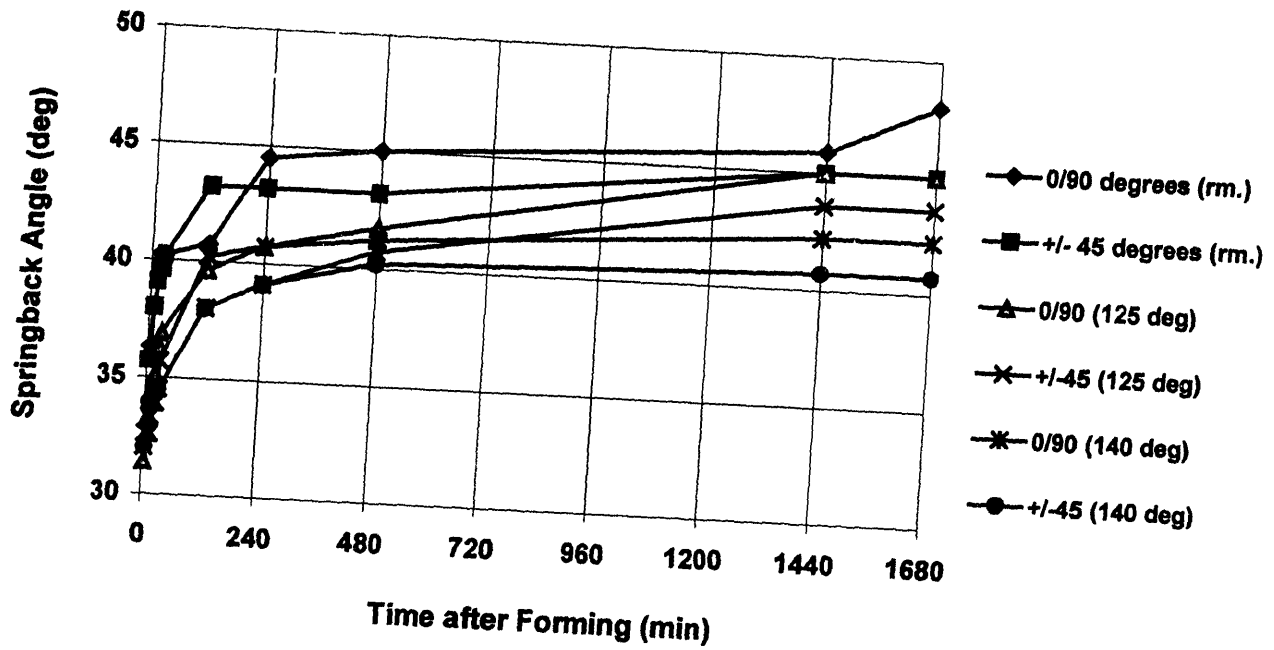


Figure B.1 Results of 16 Ply 0/90 vs. ±45 Lay-ups Springback Experiments.

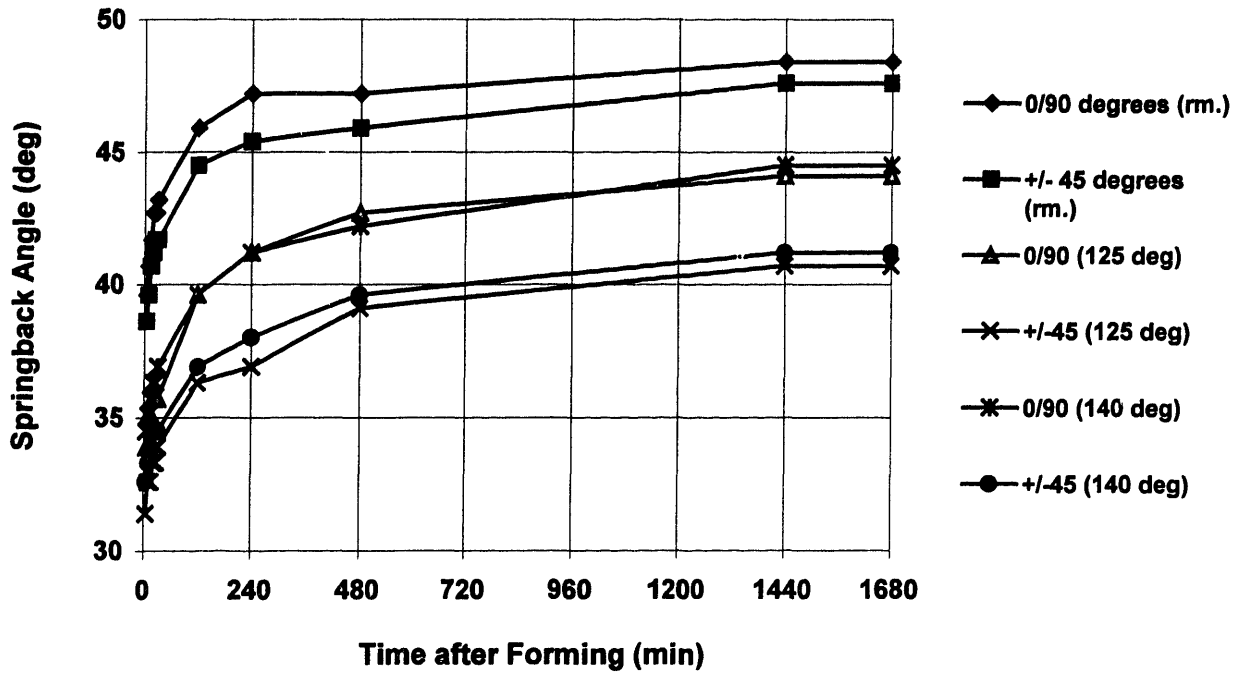


Figure B.2 Results of 24 Ply 0/90 vs. ± 45 Lay-ups Springback Experiments.

APPENDIX C

RESULTS OF 10 PLY 0/90 VS. QUASI-ISOTROPIC SPRINGBACK EXPERIMENTS

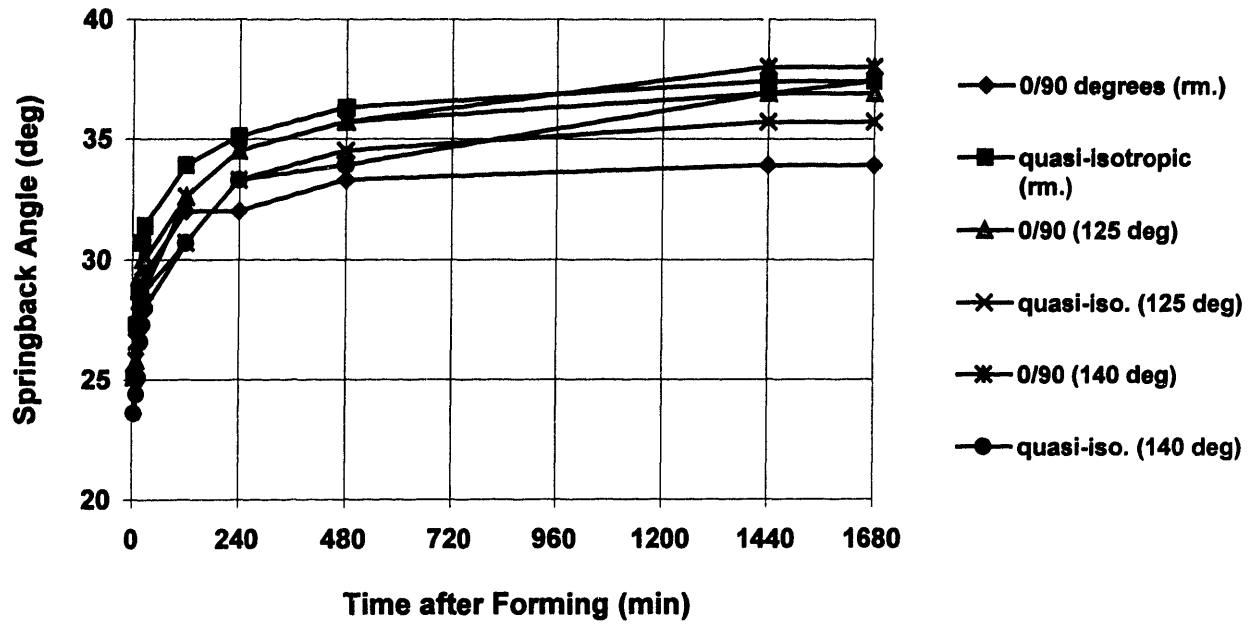


Figure C.1 Results of 10 Ply 0/90 vs. Quasi-isotropic Lay-ups Springback Experiments.

APPENDIX D

RESULTS OF 10 PLY ± 45 VS. QUASI-ISOTROPIC SPRINGBACK EXPERIMENTS

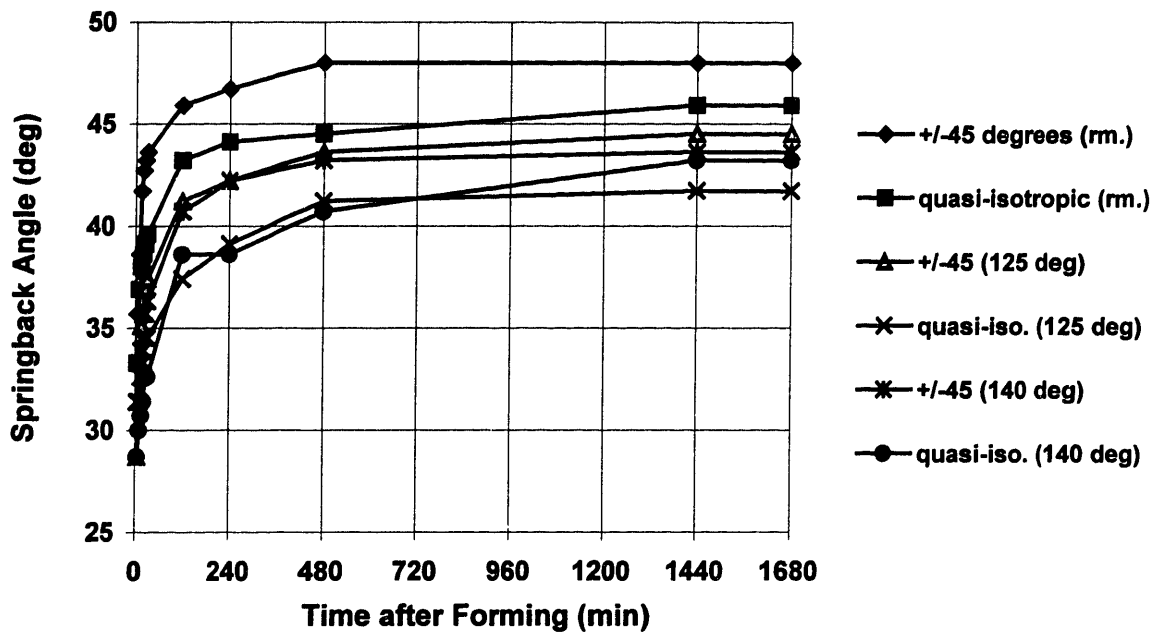


Figure D.1 Results of ± 45 vs. Quasi-isotropic Springback Experiments.

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- Li, Haorong. 1998. Forming of Advanced Thermoset Composites: Process Development and Deformation Study. Ph.D. diss., Massachusetts Institute of Technology.

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