The Formation of Advanced Composite Materials Over Complex Geometric Shapes Using Inflated Diaphragms

by

Paul J. Llamas

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Bachelor of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 9, 1997

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Author ....
Department of Mechanical Engineering
May 9, 1997

Certified by ....
Professor Timothy Gutowski
Department of Mechanical Engineering
Thesis Supervisor

Accepted by ....
Professor Peter Griffith
Chairman, Undergraduate Thesis Committee
Mechanical Engineering Department

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Abstract

An investigation of the formation of aligned composites and woven fabrics over complex geometric shapes using different forming processes has been performed. The investigation focuses on the wrinkling effects seen in aligned fibres over c-channel tools using drape and inflated diaphragm forming processes. A comparison is made to determine whether either forming process has an advantage over the other. The results show that the inflated process seems to work better relative to the drape method. However, both methods leave room for improvement. The investigation also focuses on the formation of woven fabrics over hemispheres of varying diameters to determine the angles and diagonals as well as the in-plane and inter-ply shear experienced by the fabric. The resulting angles and diagonals formed by the preset grid, drawn on the woven fabric, are then compared to those predicted by a theoretical model. The comparison between the results show good agreement.

Thesis Supervisor: Professor Timothy Gutowski
Title: Mechanical Engineering Professor

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Chapter 1

Introduction

The utilization of advanced composite materials in all types of industry has increased over the years. The advantages of composites are their unique mechanical properties and the possibility of tailoring these materials to the load requirements desired to perform a certain task. Fibre reinforced composites have a high stiffness to weight ratio which is important in weight sensitive applications such as highly sophisticated aerospace vehicles. However, the use of composites is also extending into the aircraft and automobile industries.

Despite the advantages that come with the use of composites materials, their use have been limited due to several disadvantages. One big disadvantage is that they are significantly expensive. One reason that contributes to their high cost involves the manufacturing of the composite materials themselves. The monotonous task of impregnating the matrix with the fibres to make the composite material adds significantly to the cost. The other reason involves processing the composite materials into a manufactured part. The process usually entails workers laying up the part by hand. This labor intensive process drives up the cost even higher. As a result, the costs involved in manufacturing composite parts is much more expensive than conventional metallic and plastic parts.

Designing with composites is also more complicated than with metals and simple plastics. Whereas the material properties of metals and simple plastics are clearly specified with a moderate degree of variation, composites are more like a construction of fibres and a matrix. Usually several iterations are necessary in the design procedure of load bearing structures made of composites. In order to take full advantage of the potential capacity of composites for specific purposes, the properties of yet unknown combinations or formations of available fibres and matrices must be assessed.

The challenges presented by the use of composite materials are being met in several ways. The use of automated tape lay-up and cutting techniques have cut the costs involved with the manufacturing of composite materials. The cost of manufacturing composite materials into parts has also decreased with the use of diaphragm forming. Research is also underway to determine the characteristic material properties of composites. This will make it possible to better understand the material and use it properly in the design of structures.

Diaphragm forming is a process used to eliminate the need for workers to lay up the part by hand. It involves a one step process where a flat laminate prepreg preform is placed on a tool. A silicone rubber diaphragm or diaphragms are used to form the prepreg over a tool of a given geometry. There are currently three different diaphragm forming processes being investigated. These three processes are drape, inflated diaphragm, and double diaphragm forming.

The understanding of the characteristic behaviors of both aligned and woven composites are essential for the proper use of the material. The best way to accomplish this is to develop a theoretical model that will accurately predict the deformation behavior of these composites.

There are two underlying purposes focused on in this investigation. One is to analyze the wrinkling effects seen in aligned composites when formed over a curved c-channel tool. This procedure is done using both the inflated diaphragm and drape forming processes. These results will then be compared to one another to determine whether one process has an advantage over the other and to determine whether or not there is a way to improve either process to increase its efficiency in reducing the number of defective parts formed.

Chapter 2

Theoretical Analysis

2.1 Laminate Wrinkling and Shear Displacement of Aligned Composites

Laminate wrinkling of aligned composites occurs when compressive forces created during formation causes a gross buckling deformation through the entire thickness of the laminate. Due to the severe constraints on the material's inability to be compressed, aligned composites are restricted in modes of deformation. The laminate's ability to form into complex geometries is achieved by in-plane and inter-ply shear displacements. In-plane shear occurs when adjacent fibres in the same plane slide past one another. Inter-ply shear occurs when plies slide past one another. Other shears occur in this process, such as transverse shear and longitudinal through-the-thickness shear, but are not of relative importance. The compressive forces which cause the gross bucking arise from the material compression necessary to form double curved shapes, such as in the geometry of a curved c-channel.[1]

2.2 Predicting In-Plane Shear Of Woven Fabrics

The theoretical analysis for predicting the angles and diagonals formed over a hemisphere for an n x n grid of size d is done by applying spherical trigonometry to a typical cell (i, j) that has been divided into four equal and right-handed triangles[2] (See Figure 2).

$$A_{ij} = \pi - (A_{i-1,j-1} + B_{i-1,j} + B_{i,j-1}) \tag{2.1}$$

$$a_{ij} = \operatorname{asin}(\sin A_{ij} \sin d) \tag{2.2}$$

$$b_{ij} = 2\,\mathrm{atan}\left[\tan\frac{1}{2}(d-a_{ij})\left(\frac{\sin\frac{1}{2}\left(\frac{\pi}{2}+A_{ij}\right)}{\sin\frac{1}{2}\left(\frac{\pi}{2}-A_{ij}\right)}\right)\right] \tag{2.3}$$

$$B_{ij} = 2\,\mathrm{atan}\left[\cot\frac{1}{2}\left(\frac{\pi}{2}-A_{ij}\right)\frac{\sin\frac{1}{2}(d-a_{ij})}{\sin\frac{1}{2}(d+a_{ij})}\right] \tag{2.4}$$

Initial conditions for these recurrence relations are:

$$A_{i0} = A_{0j} = B_{i0} = B_{0j} = \frac{\pi}{4} \tag{2.5}$$

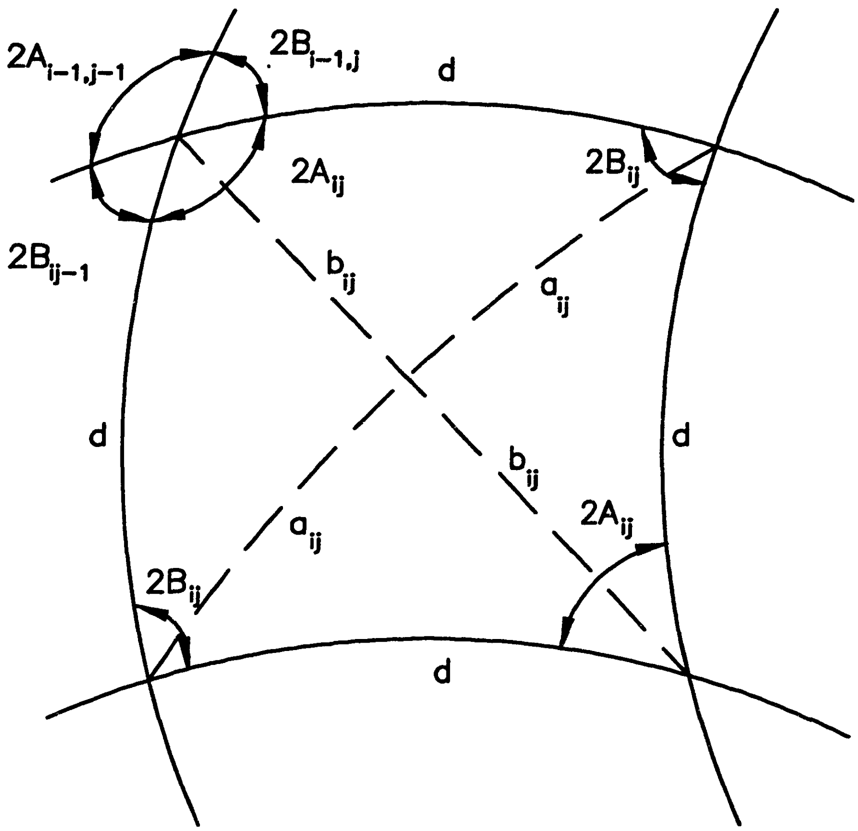


Figure 2.1: Spherical Quadrilateral

2.3 Inter-ply Shear of Woven Fabrics

A theoretical model for inter-ply shear displacement has yet to be developed. However, it is hoped that the results of this investigation will show some similarities between the inter-ply shear displacements of woven fabrics to those of aligned fibre composites. The results of this experiment will help provide insight into the characteristic behavior of inter-ply shear displacements of woven fabrics. A mathematical algorithm to properly predict inter-ply shear displacement of woven composites will be further assisted with the results obtained from this investigation.

Chapter 3

Experimental Procedure

There are two sets of experiments conducted. One set of experiments focuses on the wrinkling effects of aligned fibre composites using the inflated diaphragm and drape forming processes. The second set of experiments focuses on the mapping behavior of woven fabrics over hemisphere tools using solely the double diaphragm forming method.

3.1 Formation Of 0°/90° Aligned Fibre Composites On A Curved C-channel

3.1.1 Graphite/Epoxy Aligned Fibre Composites Over A Curved C-channel

The test specimens used in this set of experiments consisted of 6in.x12in. prepreg aligned fibre composites varying from two plies to eight plies in thickness. The type of composite used is Toray 3900 that comes in a roll that measures six inches in width.

3.1.2 Sample Preparation

The Toray composite roll needs to first be removed from the lab freezer and allowed to three hours to properly thaw to room temperature before its packaging can be opened to prepare the samples. Once the composite material is thawed out, it is placed on a thin elevated rod to properly support it while the samples are cut. When the desired quantity of plies are cut, they are carefully layered in a 0°/90° orientation. One ply is placed over the other after removing the protective paper backing from the composites. Once the desired number of plies is achieved, they are pressed together using a small hand roller. Two sets of two, four, six, and eight plies are made for a total of 8 samples.

These samples are then precut to a c-shaped geometry to properly form over the curved c-channel tool to be used in the this experiment. One set of samples is used in the inflated diaphragm forming experiments while the second set is used for the drape forming experiments.

3.1.3 Inflated Diaphragm and Drape Forming Apparatuses

The purpose for this set of experiments is to determine whether the inflated diaphragm or double diaphragm process has an advantage over the other and to observe the wrinkling effects experienced by the composite samples. The inflated diaphragm forming apparatus consists of an adjustable tool platform ring with a silicone rubber diaphragm attached, vacuum ports, an aluminum ring with a silicone rubber diaphragm attached, and a transparent plexiglass tube. One diaphragm is located underneath the adjustable tool platform ring. The other is located underneath the cap of the apparatus (See Figure 3.1).

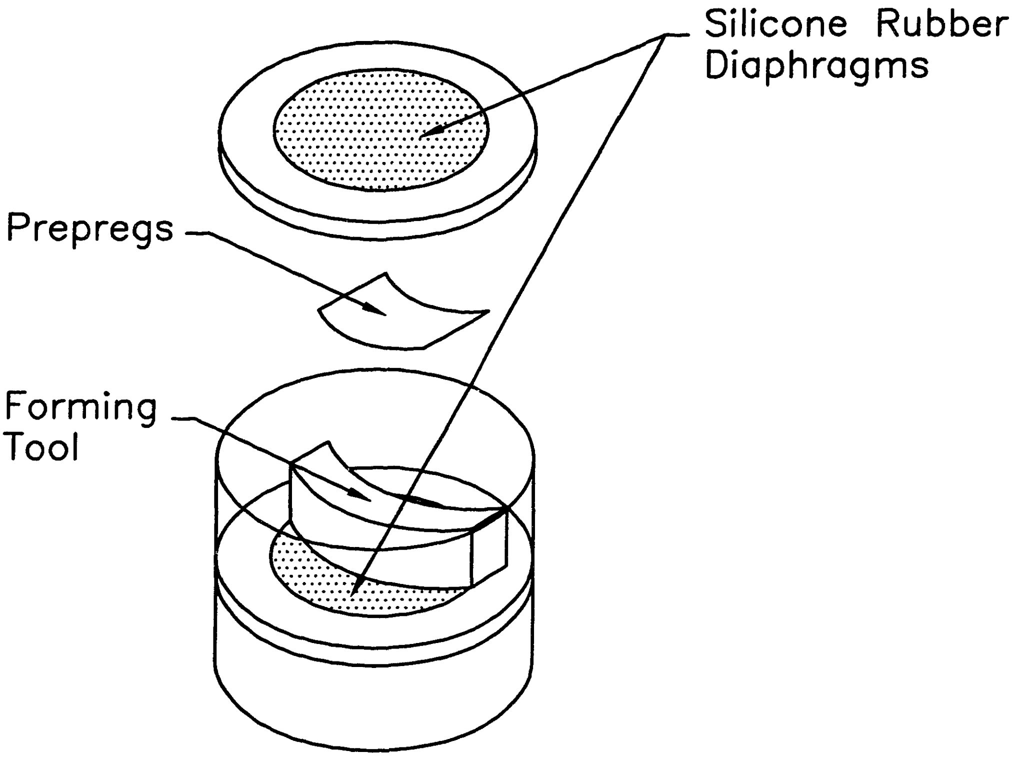


Figure 3.1: Inflated Diaphragm Apparatus

The drape forming apparatus consists of an adjustable tool platform, vacuum ports, an aluminum ring with a silicone rubber diaphragm attached and an aluminum cylinder. The prepreg is then placed on the tool followed the aluminum ring with the silicone rubber diaphragm (See Figure 3.2).

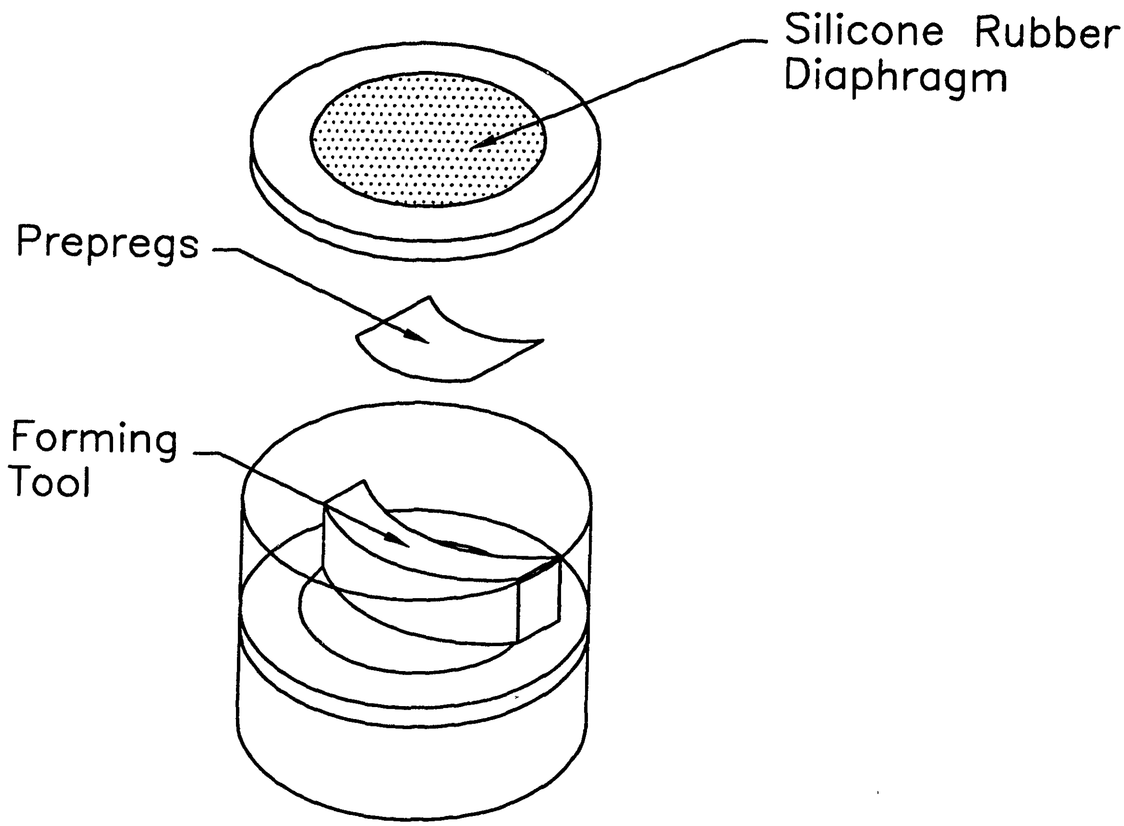


Figure 3.2: Drape Forming Apparatus

3.1.4 Diaphragm Forming Testing Procedure

3.1.4.1 Inflated Diaphragm Forming Testing Procedure

To make the part using the inflated diaphragm process, the prepreg preform is placed directly on the tool and the assembly is bolted down. A vacuum is then created to cause the upper diaphragm to have contact with the cap of the apparatus. The next step is to create a second vacuum inside the chamber causing the lower diaphragm to move upward. This results in the lower diaphragm to lifting up the prepreg until the diaphragm has reached maximum contact with the upper diaphragm. This procedure is done to support the prepreg. Once this step is complete, the vacuum on the upper diaphragm is removed causing it move downward applying pressure against both the prepreg and lower diaphragm. This process continues until the upper diaphragm has full contact with the tool. As a result of this process, the prepreg is formed over the tool as well (See Figure3.3). This procedure is done for two, four, six, and eight plies. The wrinkling area is recorded for each sample.

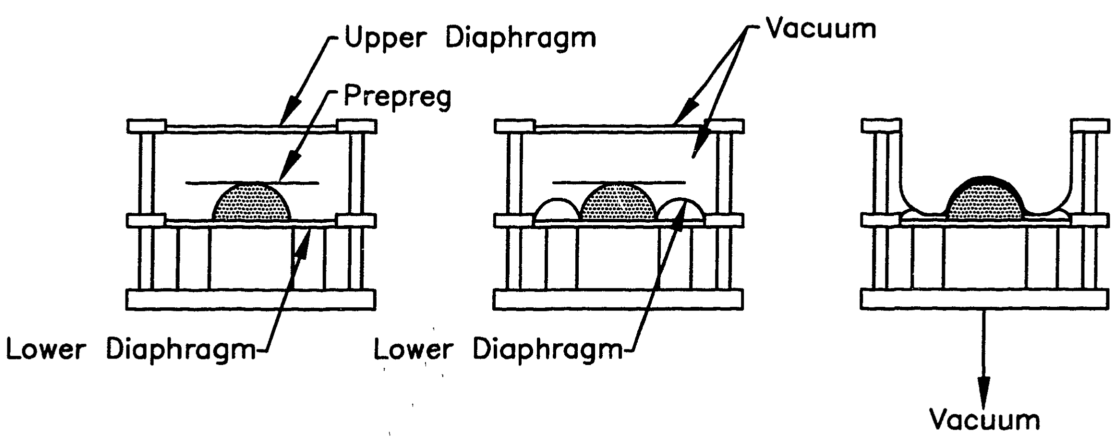


Figure 3.3: Inflated Diaphragm Forming Process

3.1.4.2 Drape Forming Testing Procedure

To make the parts using the drape forming process, the prepreg is placed on the tool followed by the aluminum ring that is place on top. A vacuum is then created between in the chamber so that the diaphragm deforms. This process, which deforms the diaphragm over the tool, deforms the prepreg in over the tool as well.(See Figure 3.4) This procedure is carried out for two, four, six, and eight plies. The wrinkling area is recorded for each sample.

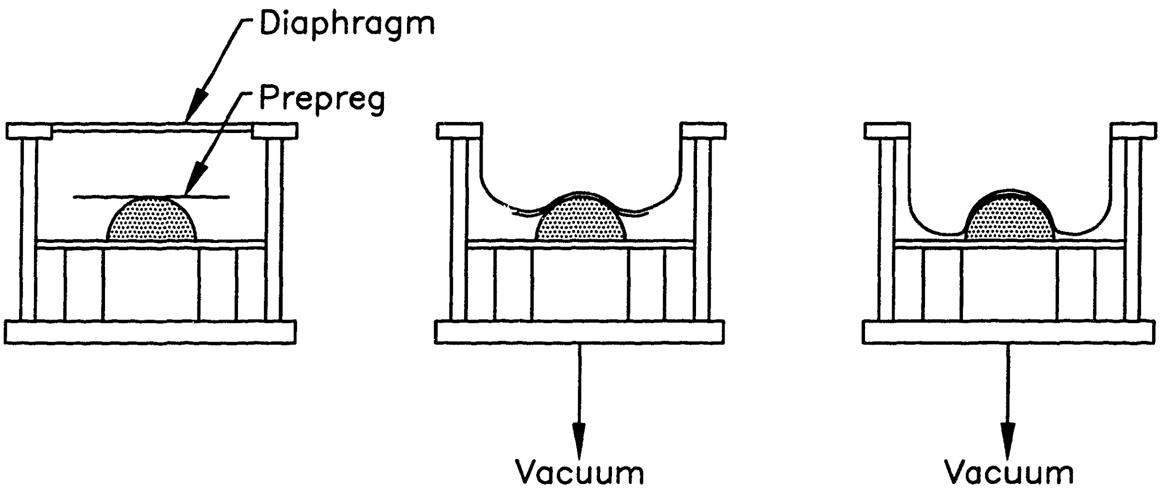


Figure 3.4: Drape Forming Process

3.2 Formation of Woven Fabric Materials Over Hemispheres

3.2.1 Charcoal Fiberglass Woven Fabric Test Samples

The test specimens used in this set of experiments consist of charcoal fiberglass plain weave fabric. Two samples are made to be formed over hemisphere tools of 4.75 in. and 9 in. in diameter while four samples are made to be formed over a 7in. diameter hemisphere for a total of eight samples. The samples are cut using templates made available in lab. An X and Y axis are then drawn as well as a 0.5in x 0.5in grid on all of the samples (See Figure 3.5). In marking the gird, it was realized that the weave of the fabric did not form perfect squares. In fact, in one direction, it takes eight squares on the fabric to make the 0.5 inch grid while in the other direction it takes nine squares to make 0.5 inch grid. This fact may be important in the future when analyzing the results of the experiments.

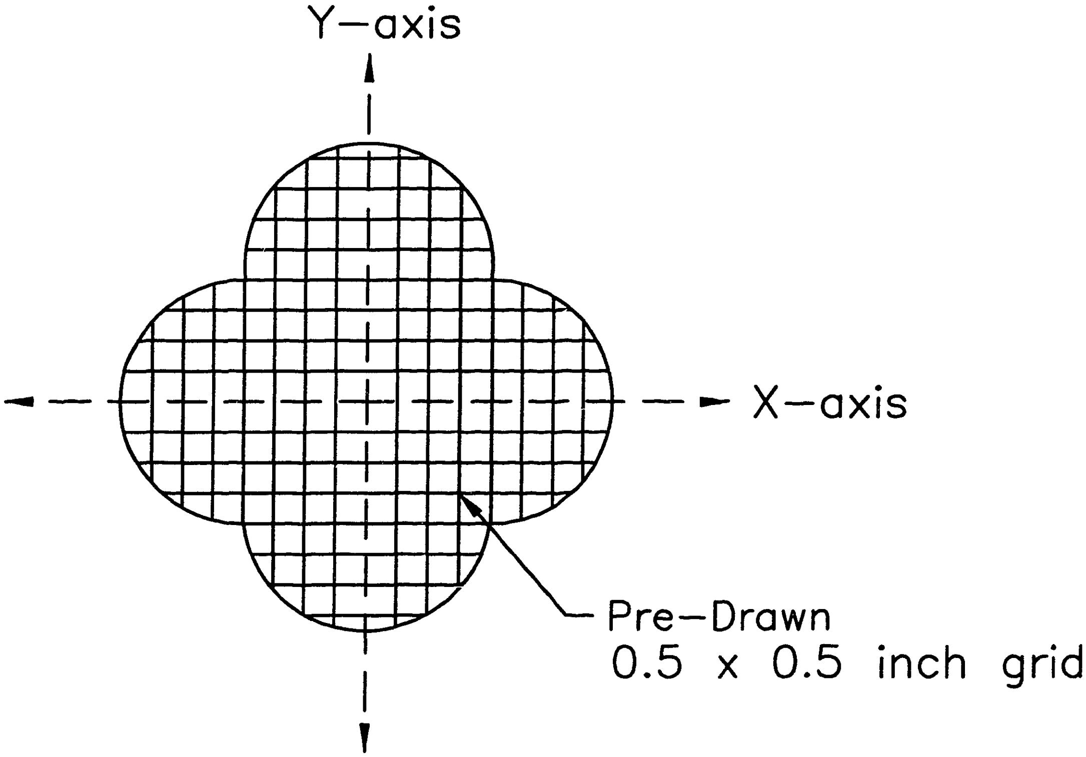


Figure 3.5: Woven Fabric Test Sample

3.2.2 Testing Procedures for Woven Fabrics

3.2.2.1 Testing Procedures to determine the mapping over a hemisphere

Using the double diaphragm method described in section 3.1.4.2, a plain weave woven fabric sample is formed over a hemisphere. This results in the deformation of the pre-drawn 0.5in x 0.5in grid. The angles and diagonals formed in each 0.5in x 0.5in square are measured and recorded. This procedure is done for hemispheres of diameters 4.75in., 7in., and 9in.

3.2.2.2 Testing Procedures to determine the In-Plane Shear

Using the double diaphragm method described in section 3.1.4.2, a woven fabric sample is formed over a hemisphere. This results in the deformation of the pre-drawn 0.5in. x 0.5in. grid. The distances between each marked fibre, along the edge of the hemisphere, are then measured and recorded. This procedure is done for the hemispheres of diameters 4.75in., 7in., and 9in.

3.2.2.3 Testing Procedures to determine the Inter-Ply Shear Displacement

Using the double diaphragm method described in section 3.1.4.2, two of the samples are placed in between the two diaphragms in a $0^\circ/45^\circ$ orientation. Even though they are in a $0^\circ/45^\circ$ orientation, their grids are drawn so that they are overlapping each other. The two samples are formed over the 7in. diameter hemisphere. A zoom in of the points marked to measure displacement between the inter-ply grids is shown in figure 3.5. The inter-ply shear displacement is measured by measuring the displacement of a marked point on the uppermost sample from the mark point of the underlying sample where the point on the underlying sample is considered the point of origin. The direction of displacement is marked by negative and positive X and Y direction, as marked on figure 3.6. These measurements are recorded.

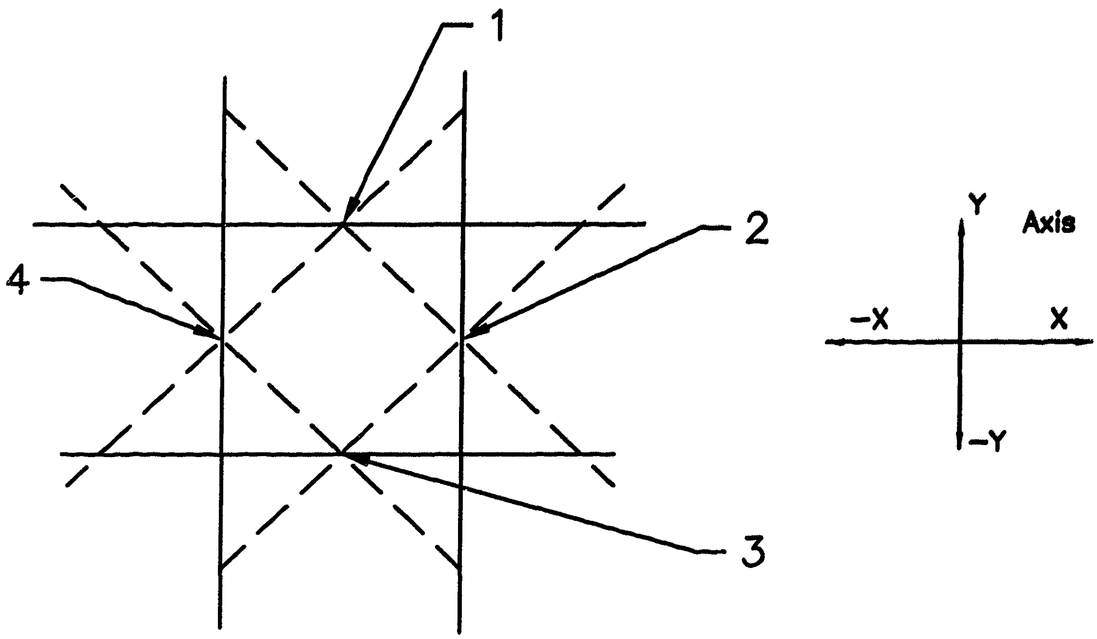


Figure 3.6: Zoom In of Grids on the Plies and Points Marked to Measure Displacement

Chapter 4

Results

4.1 Results of Deformed Aligned Composites Over a Curved C-Channel

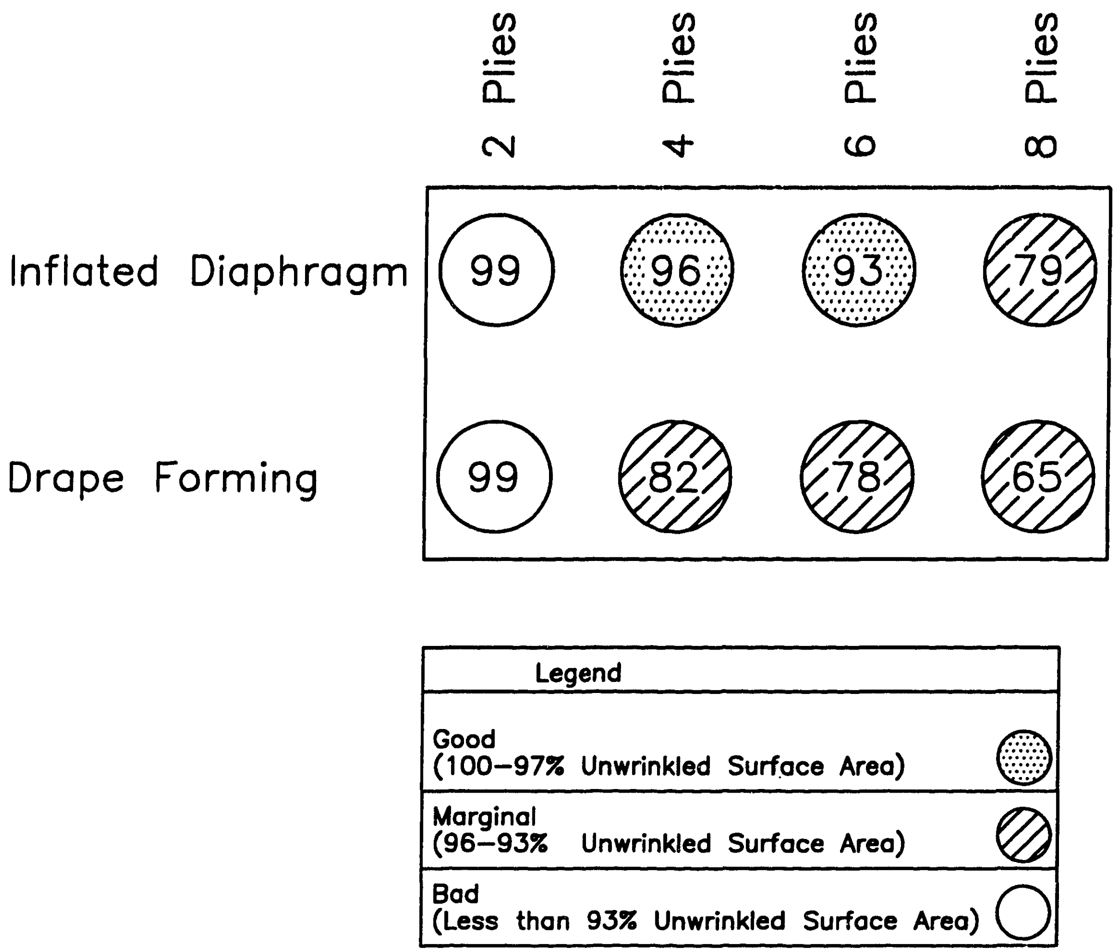


Figure 4.1: C-channel Deformation Results

Figure 4.1 shows the percentage of unwrinkled surface area for each number of plies for both the inflated diaphragm and drape forming methods. The results of the drape forming method were done by Jerrod Berlinger, an undergraduate research opportunities program (UROP) student. It was arbitrarily determined that parts with 97% or higher of unwrinkled surface area was considered a good part, anything between 96% and 93% was considered a marginally good part, while anything less that 93% was considered a bad part.

4.2 Results of Angles Formed Over Hemispheres of Varying Diameters

Figures 4.2, 4.3, and 4.4 show the angles formed by the woven fabrics' predrawn 0.5in. x 0.5in. grid in one quadrant for every hemisphere used. Each angle measured is marked on the figures. Each square shows the angles obtained from the experimental data as well as the theoretical. The theoretical results were done using a C Language program written by Haorong Li, an MIT graduate student, based on the theoretical model described in section 2.2.

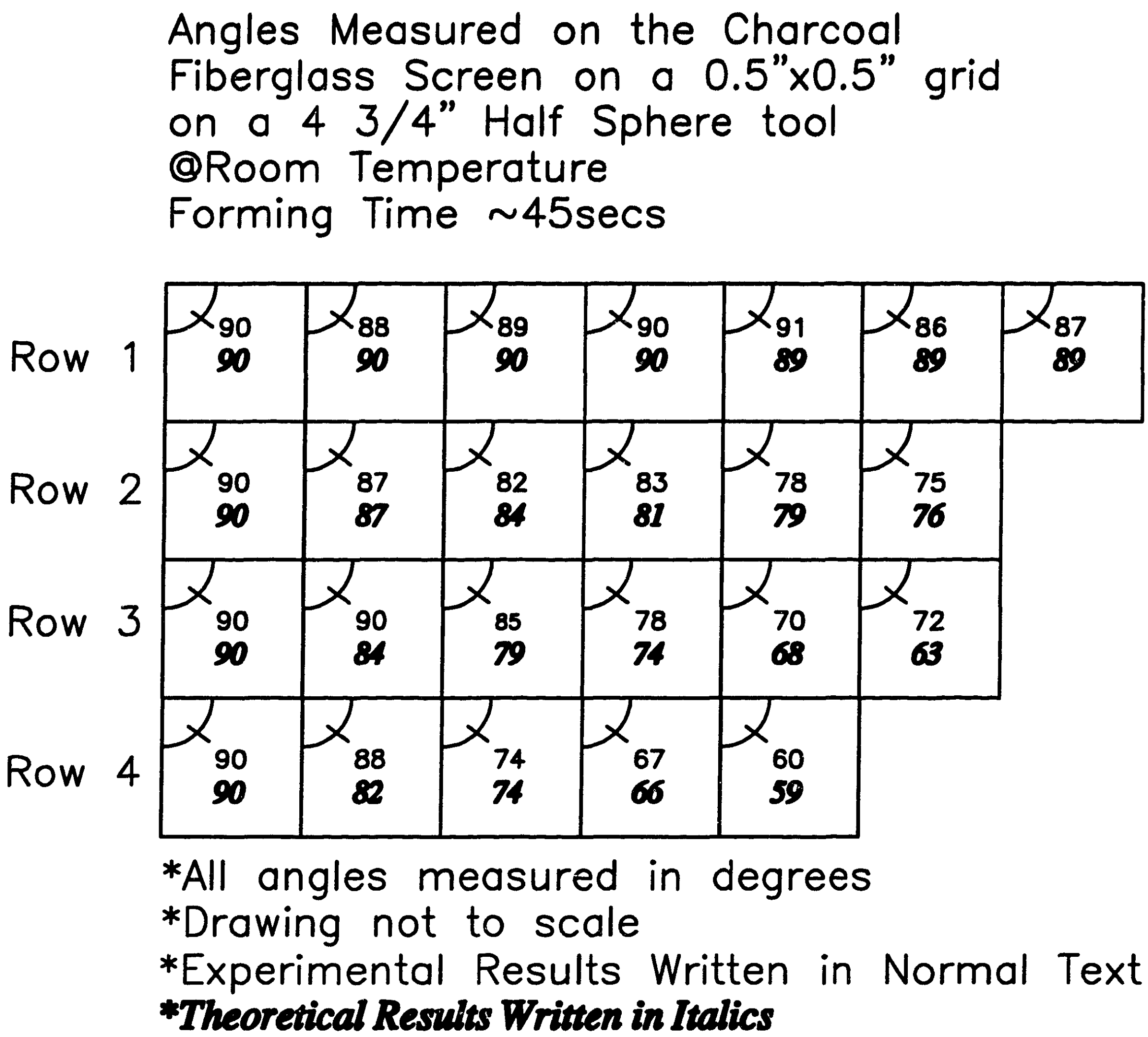


Figure 4.2: Angle Results of 4.75 inch Diameter Hemisphere

Row 1	90 *90*	88 *90*	89 *90*	91 *90*	87 *90*	89 *90*	91 *90*	90 *89*	90 *89*	90 *89*
Row 2	89 *90*	87 *90*	87 *87*	85 *86*	84 *85*	82 *84*	80 *84*	79 *81*	80 *80*	
Row 3	90 *90*	87 *87*	85 *85*	83 *83*	85 *80*	77 *78*	75 *75*	72 *73*	80 *70*	
Row 4	86 *90*	90 *86*	90 *83*	80 *79*	75 *76*	75 *72*	69 *68*	70 *65*	72 *62*	
Row 5	90 *90*	89 *85*	85 *80*	78 *76*	75 *71*	71 *66*	67 *62*	57 *57*		
Row 6	90 *90*	90 *84*	81 *78*	77 *72*	69 *66*	62 *60*	63 *55*			
Row 7	90 *90*	90 *83*	76 *75*	75 *68*	66 *62*	65 *55*				
Row 8	90 *89*	87 *81*	77 *73*	73 *65*	66 *57*					
Row 9	90 *89*	90 *80*	75 *71*	88 *62*						

Angles Measured on the Charcoal Fiberglass Screen on a 0.5"x0.5" grid on a 7" half Sphere tool
●Room Temperature
Forming Time ~60secs
*All units measured in inches
*Drawing not to scale
*Experimental Results Written In Normal Text
****Theoretical Results Written In Italics***

Figure 4.3: Angle Results of 7 inch Diameter Hemisphere

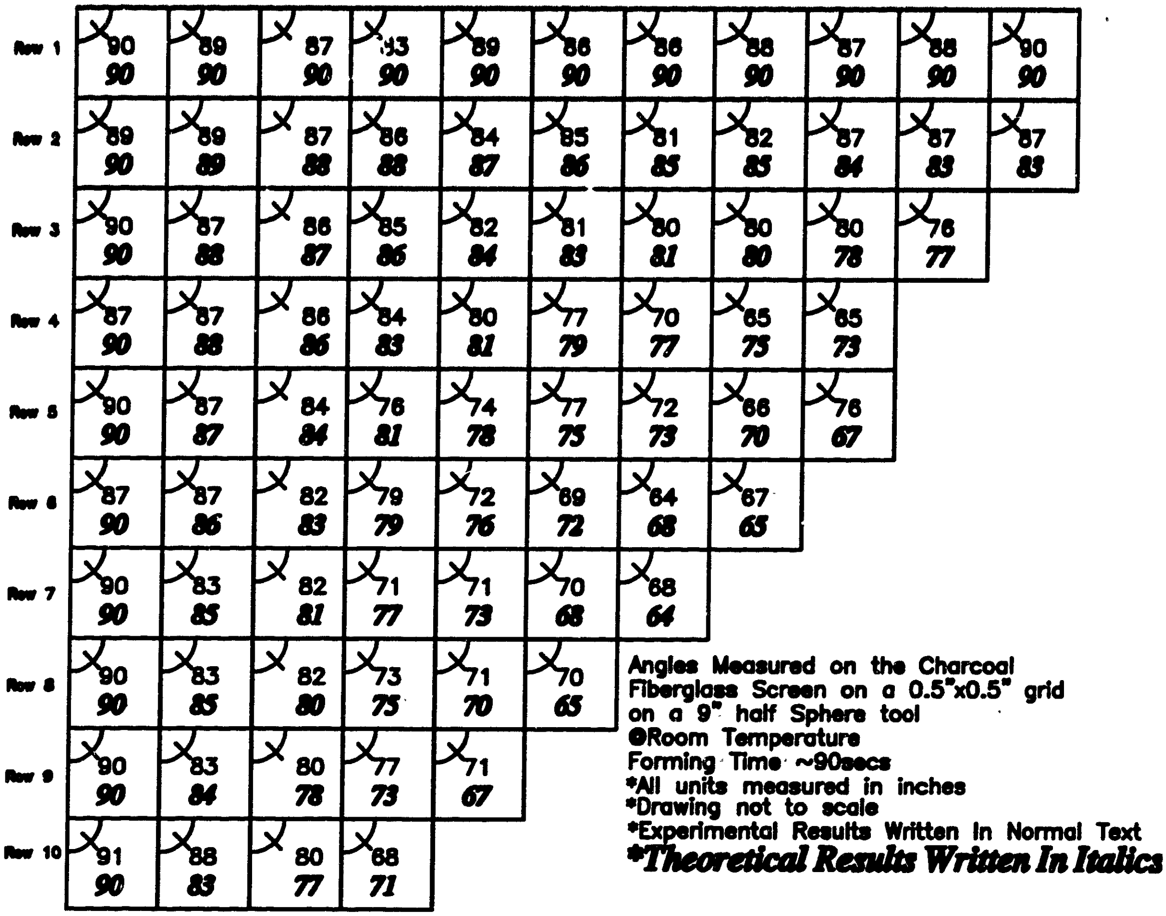


Figure 4.4: Angle Results of 9 inch Diameter Hemisphere

4.3 Results of Diagonals Formed over Hemispheres of Varying Diameters

Figures 4.5, 4.6, and 4.7 show the diagonals formed by the woven fabric's predrawn 0.5in x 0.5in grid in one quadrant for every hemisphere used. Each diagonal measured is marked on the figures. Each square shows the diagonals obtained from the experimental data as well as the theoretical.

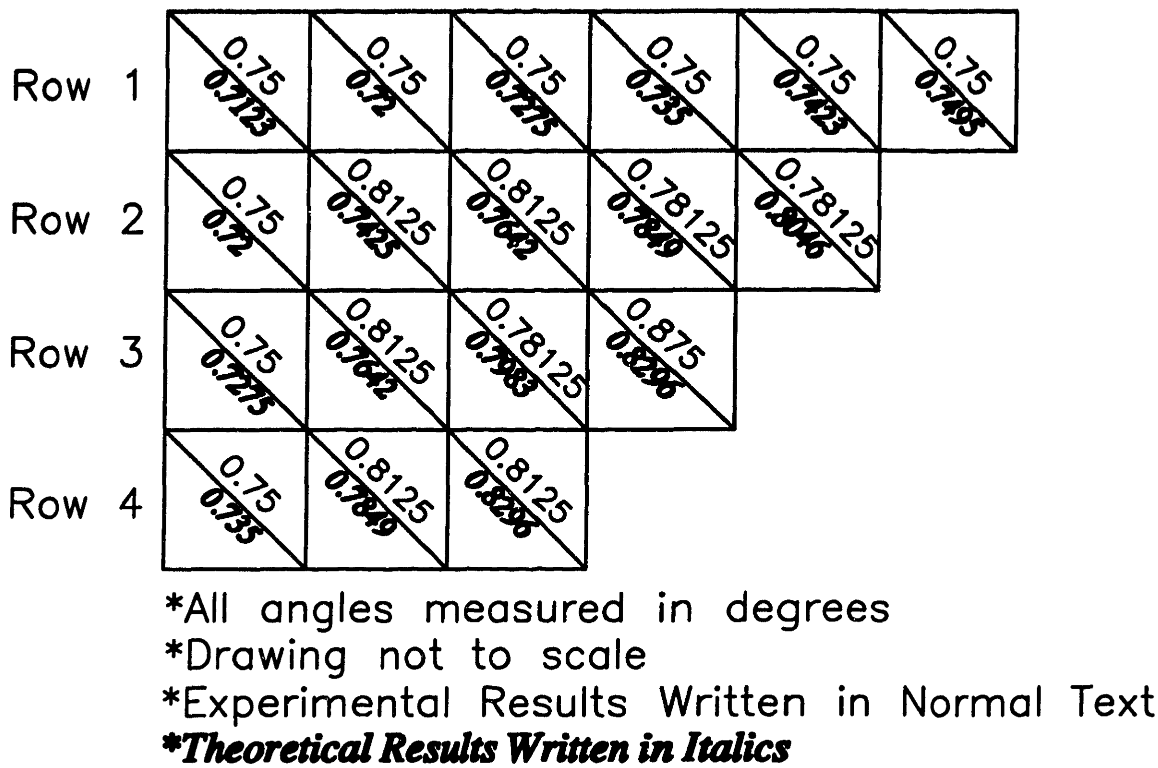


Figure 4.5: Diagonal Results for the 4.75 inch Diameter Hemisphere

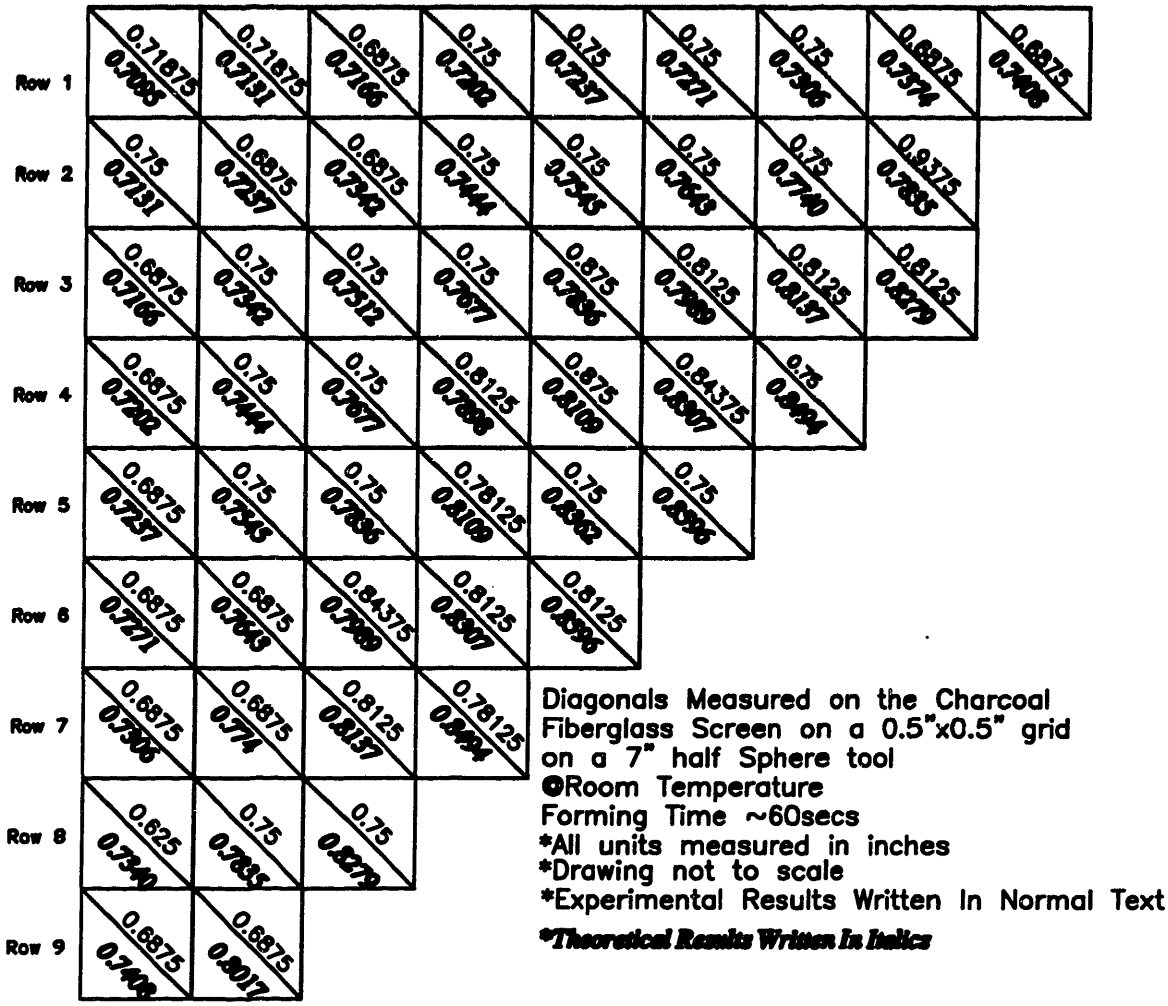


Figure 4.6: Diagonal Results for the 7 inch Diameter Hemisphere

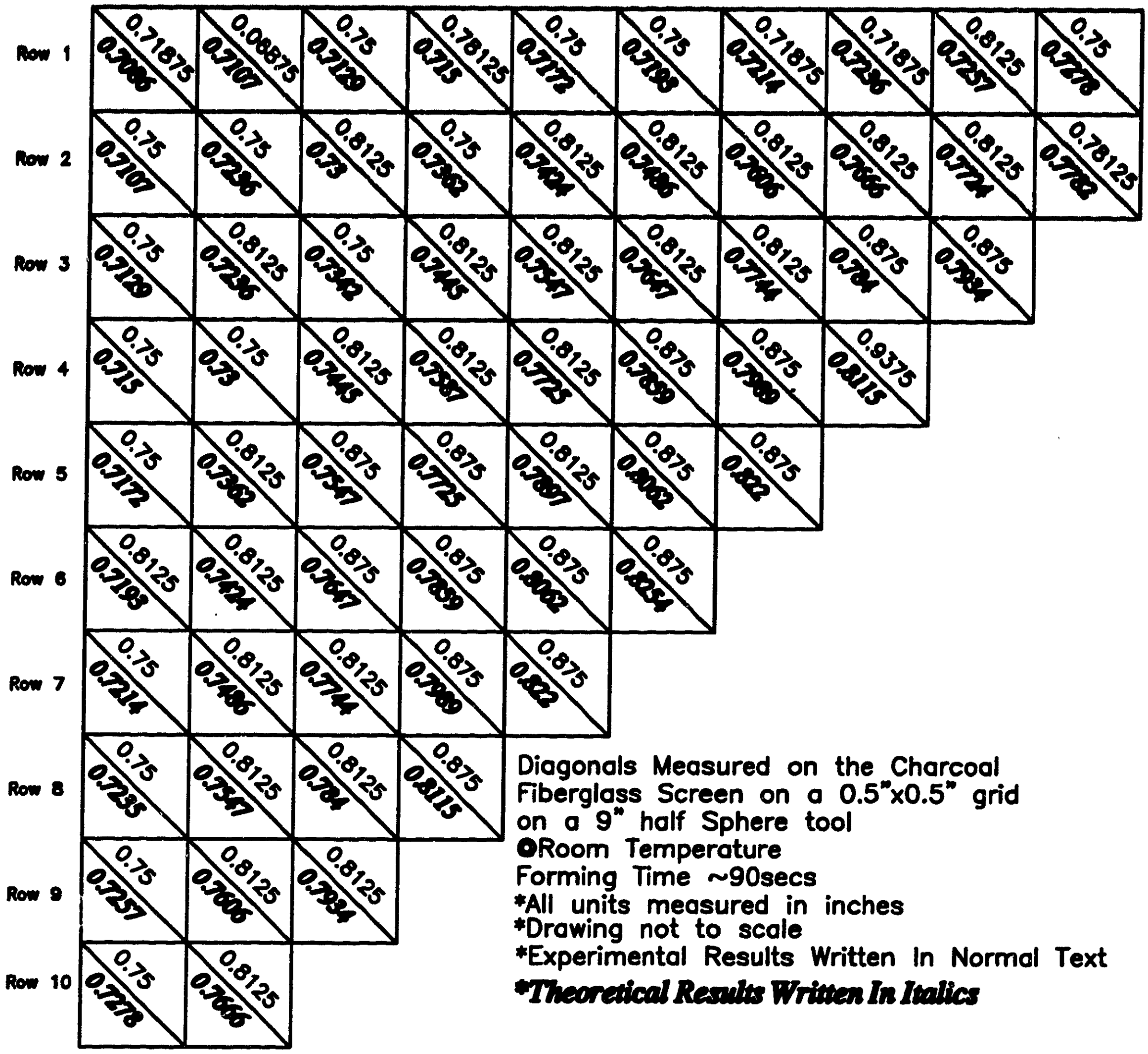


Figure 4.7: Diagonal Results for the 9 inch Diameter Hemispheres

4.4 Results of In-Plane Shear for Woven Fabrics

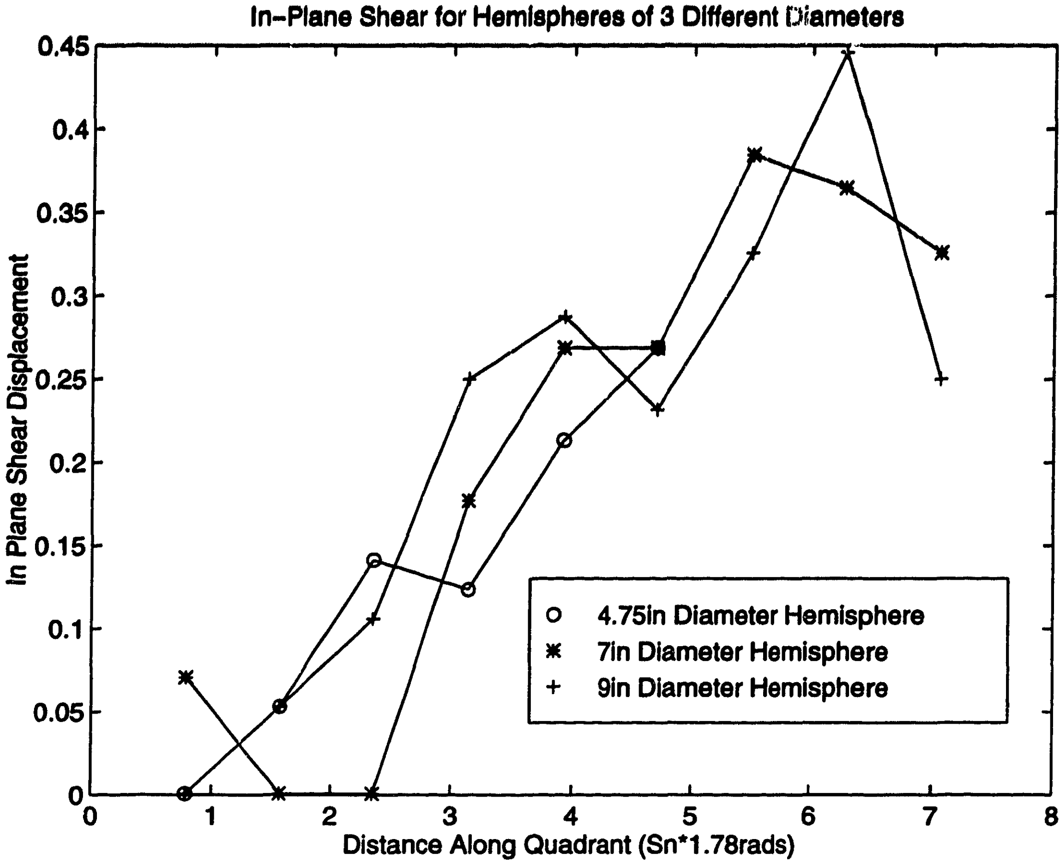


Figure 4.8: In-Plane Shear of Woven Fabric for Varying Diameter Hemispheres

This graphical analysis of the in-plane shear is made possible using the data obtained in Appendix A. The graph shows that the in-plane shear displacement for three hemispheres of varying diameters.

4.5 Results of Inter-Ply Shear Displacement

	Column1	Column2	Column3	Column4	Column5	Column6	Column7
Row 1	0,-0.03125	0.0156,-0.0156	0,0	0.03125,0	0.09375,0	0,0	0.1875,0.03125
Row 2	0,-0.046875	-0.0313,-0.0313	-0.0625,0	0.03125,0	0.125,-0.03125	0.09375,-0.3125	0.21875,0.0625
Row 3	-0.04675,-0.063	-0.04675,-0.063	-0.0625,-0.031	0,0	0.0625,0.0625	0.125,0.09375	0.15625,0.25
Row 4	-0.125,-0.04688	-0.1094,-0.047	-.15625,.03125	-0.125,0.03125	0,0.03125	0,0.09375	0.0625,0.34375
Row 5	-0.125,-0.125	-.141,-0.125	-0.1875,0	-.15625,0.0625	-0.094,0.094	-0.094,0.219	-0.094,0.40625
Row 6	-0.078,-0.109	-0.1875,-0.1875	-0.156,-.09375	-0.25,0.0625	-0.1875,0.15625	-0.1875,0.2188	-0.3125,0.375
Row 7	-0.125,-0.25	-0.25,-0.25	-0.281,-0.1563	-0.1875,-0.125	-0.15625,0.094	-0.625,0.25	
Row 8	-0.15625,-0.313	-0.375,-0.4688	-0.5,-0.375	-0.46875,-0.188	-0.375,0.03125	-0.40625,0.125	
Row 9	-0.3125,-0.469	-0.5,-0.5	-0.625,-0.5				

Table 4.1: Inter-ply Displacement Measurements

Table 4.1 shows the inter-ply shear displacement results for the woven fabrics used in this set of experiments. The results show the X and Y direction of displacement in inches for a marked point on the upper sample from its initial starting point. The numbers shown are the coordinates of the marked point from its point of origin. The point of origin is marked by a point on the lower sample which the point on the upper sample overlaps before forming (refer to figure 3.6). The two samples are formed over a seven inch diameter hemisphere. These results are merely for future reference since there is no theoretical model yet developed for this type of displacement. However, it is hoped that this data may help in the development of a model that properly predicts this type of shear.

Chapter 5

Discussion and Conclusions

5.1 Inflated and Drape Forming Methods

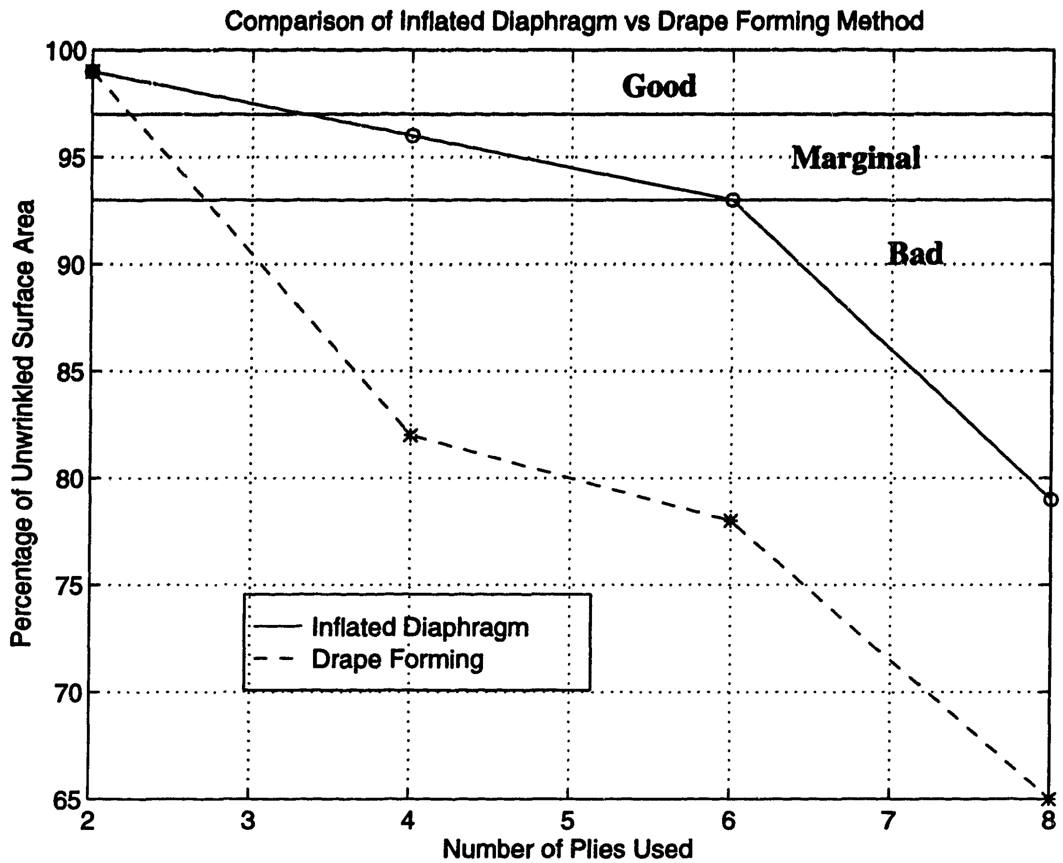


Figure 5.1: Graphical Analysis of the Inflated and Drape Forming Methods

Figure 5.1 shows a graphical plot of the results for both the inflated and drape forming procedures used to form the aligned composite samples over a curved c-channel. The graph relates the percentage of unwrinked surface area of the part formed versus the number of plies used in each part. The results of both methods are plotted. It seems that the inflated diaphragm method shows the most promising results relative to the drape forming method. However on a broader scope, neither method seems to present outstanding results.

Even though the results for either method do not look too promising, the observations made while performing the experiments lead to some interesting conclusions. For example in the inflated diaphragm forming process, the diaphragms themselves seem to play a significant role in the wrinkling of the aligned composites. Observations show that the diaphragms do not fully inflate but rather only contact the prepreg on its ends. As a result of only the prepreg's ends having contact with the diaphragms, the prepreg experiences compression forces from the diaphragms. This can lead to premature buckling not brought about by the prepreg forming over the curved c-channel. This is the exact opposite of the diaphragms' purpose. Their purpose is to provide tension in the prepreg as is forms over the curved c-channel. What needs to be done to alleviate this problem is to form the diaphragms in such a way such that they have full contact with the prepreg rather than just its ends. This way, the level of premature buckling by the diaphragms is diminished. Ways to improve this method are currently underway but are not a part of this investigation.

In observing the drape forming process, it seems that the diaphragm does not provide enough tension in the prepreg to avoid buckling. This may be the reason why the results for this set of experiments did not prove too promising. One suggestion is put the diaphragm under tension while having contact with the prepreg before beginning to create a vacuum. With the diaphragm in tension, the prepreg may undergo the same tension. This may be beneficial in offsetting the buckling forces endured by the prepreg while forming over the curved c-channel.

5.2 Comparing Theoretical and Experimental Results of Woven Fabrics

Table 5.1: Average Percent Error and Standard Deviations of Angles Formed

Diameter of Hemisphere (inches)	Average Percent Error (%)	Standard Deviation
4.75	0.0263	0.0299
7	0.0483	0.0713
9	0.0324	0.0309

Table 5.2: Average Percent Error and Standard Deviations of Diagonals Formed

Diameter of Hemisphere (inches)	Average Percent Error	Standard Deviation
4.75	0.0335	0.0212
7	0.0554	0.0445
9	0.0633	0.0325

Tables 5.1and 5.2 show and an overall average percent error and standard deviation between the theoretical and experimental results of the angles and diagonals formed over three hemisphere tools by the woven fabric used in this set of experiments (See Appendices C and D). The graphical data used to obtained these percentages and deviations can be seen in Appendices A and B. The tables show that average percent errors for the diagonals formed by the woven fabric are higher than those of the angles. This can be attributed to the fact that when measuring the diagonals, the plain weave of the fabric is not set as perfect squares as explained in section 3.2.2. However, the C Language program used to determine the theoretical results assumes that the plain weave is set as perfect squares. As a result of this assumption, the percentage error between the experimental and theoretical results of the diagonals is higher relative to the percentage errors for the angles. Another reason for this is that the angles measured experimentally are the same angle as the ones

marked by the theoretical data. Hence, there is a more precise correlation between the experimental and theoretical angle measurements than compared to the data obtained for the diagonals. So what does all this say about the accuracy of the theoretical model? Well looking at the percentage errors of both the angles and diagonals, they are substantially low. Even though it would be wise to use the data for the angles as the main factor for the deciding the accuracy of the theoretical model, in this case it is easy to see that the theoretical model agrees with the experimental results to a high degree of precision.

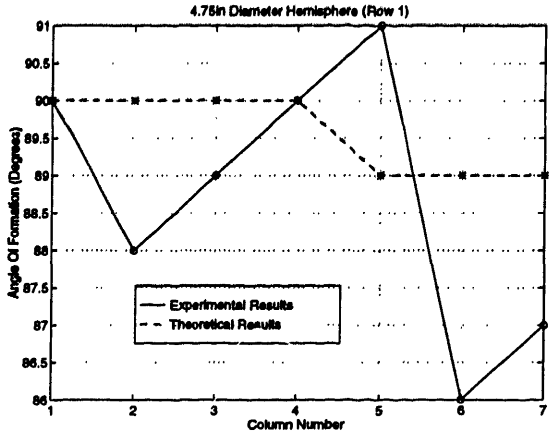
5.3 In-Plane Shear Displacement of Woven Fabric

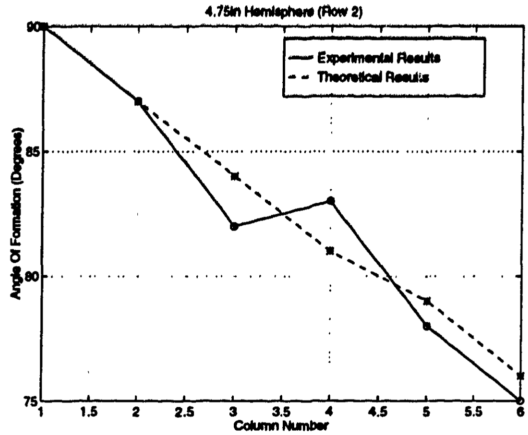
Looking back at figure 4.8 for the in-plane shear displacement of the woven fabrics samples formed over three varying hemispheres, we see that the plots are somewhat similar to the shear displacement seen in previous in-plane shear experiments done for aligned fibre composites.[3] However, these results alone do not conclusively prove that the in-plane shear behavior characteristics for both aligned fibre and woven composites are alike. It seems that the in-plane shear displacement are higher than those seen in the aligned fibre composites. One reason may be because of the fact that the woven fabric used had no resin and so it was able do displace easier. Nevertheless, further experimentation must be done to investigate this phenomenon.

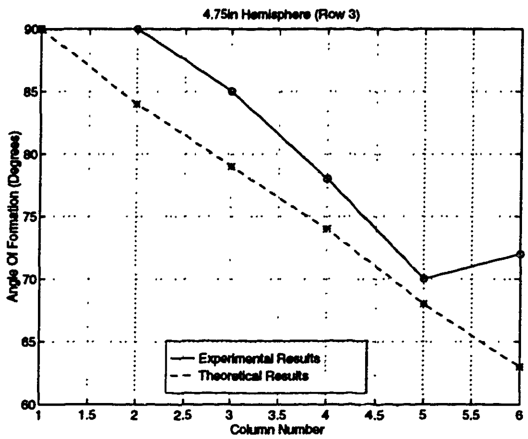
Appendix A

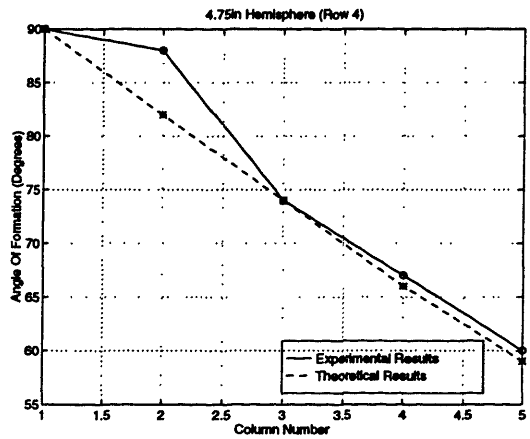
Angle Results of The Woven Fabric

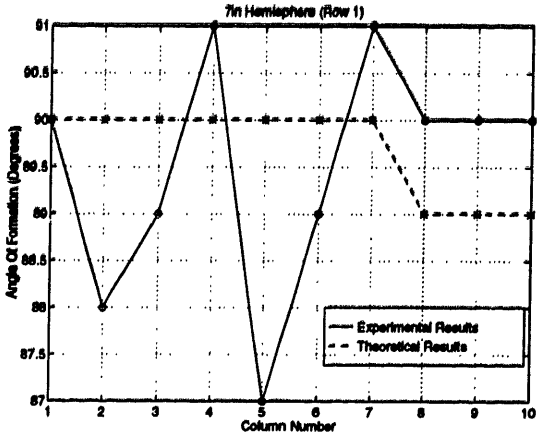
A.1 Experimental vs. Theoretical Angle Results

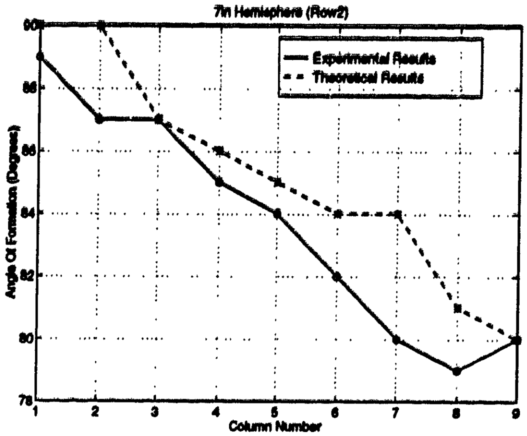


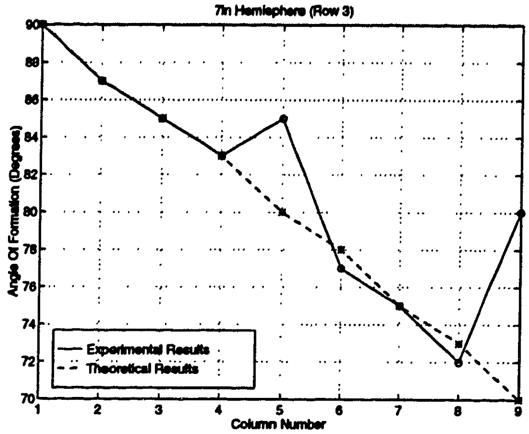


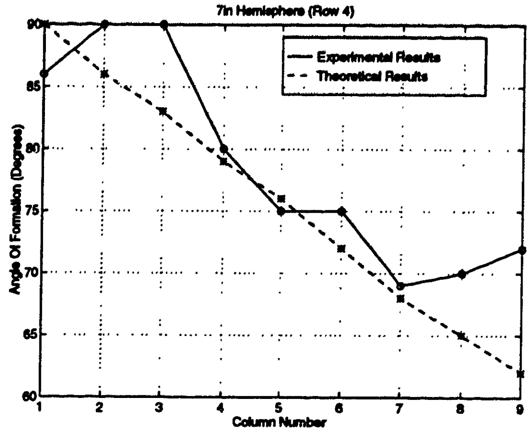


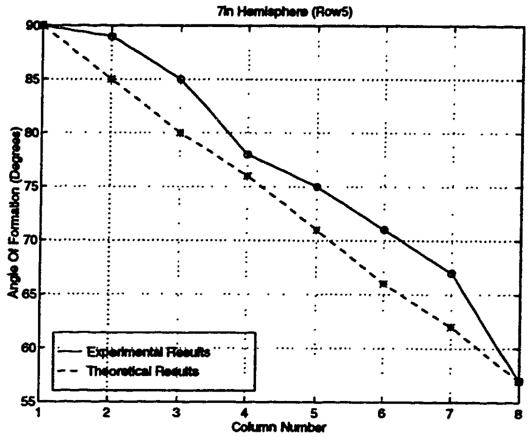


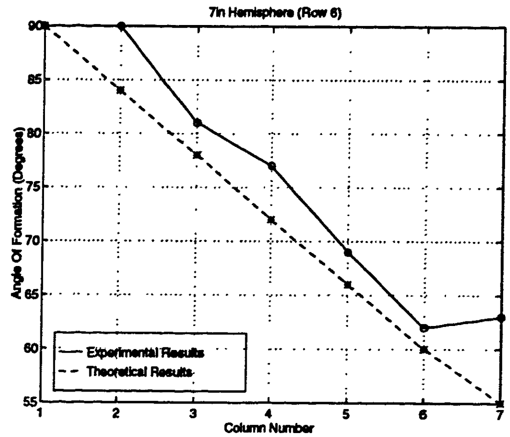

7in Hemisphere (Row 1)
Angle Of Formation (Degrees)
Column Number
Experimental Results
Theoretical Results

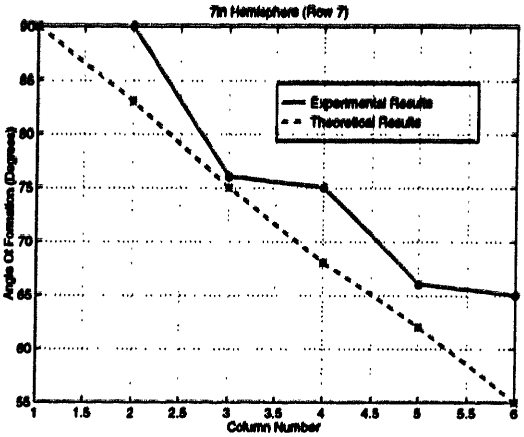

7in Hemisphere (Row2)
Angle Of Formation (Degrees)
Column Number
Experimental Results
Theoretical Results

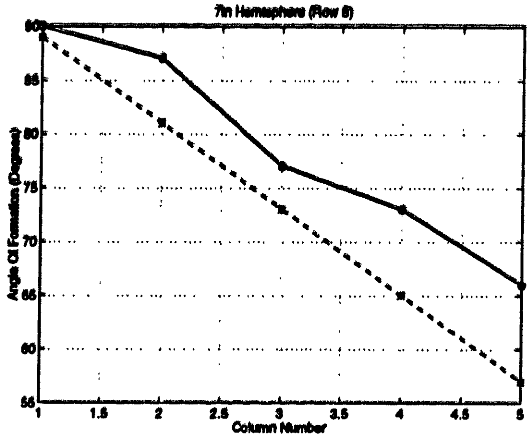

7in Hemisphere (Row 3)
Angle Of Formation (Degrees)
Column Number
Experimental Results
Theoretical Results

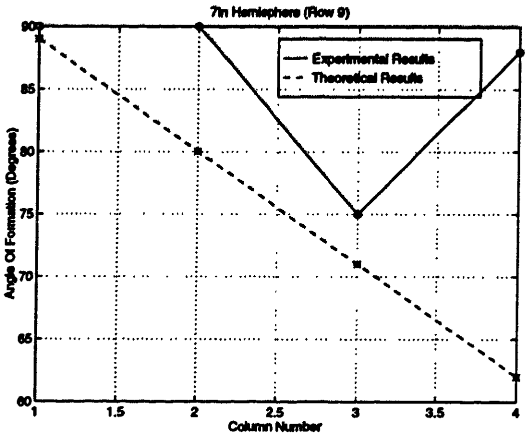

7in Hemisphere (Row 4)
Angle Of Formation (Degrees)
Column Number
Experimental Results
Theoretical Results

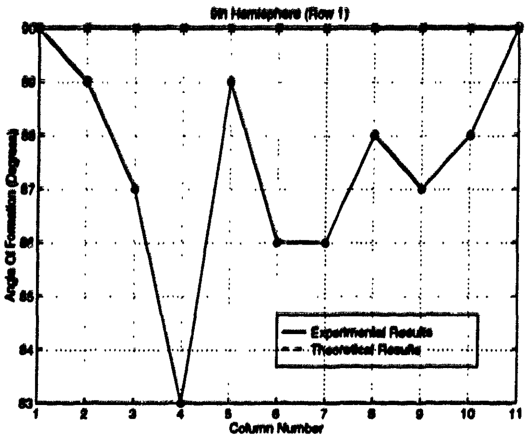

7in Hemisphere (Row5)
Angle Of Formation (Degrees)
Column Number
Experimental Results
Theoretical Results

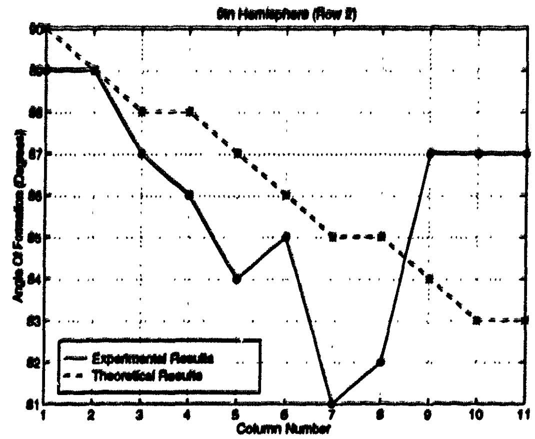

7in Hemisphere (Row 6)
Angle Of Formation (Degrees)
Column Number
Experimental Results
Theoretical Results

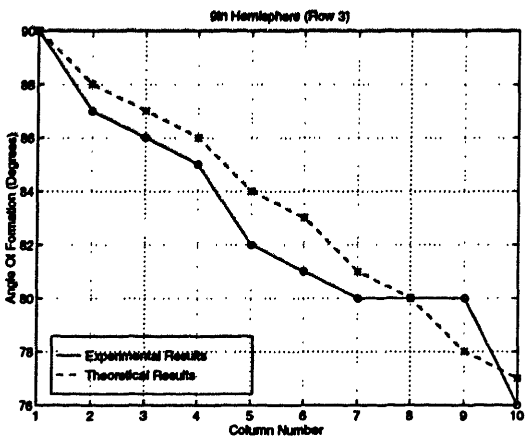

7in Hemisphere (Row 7)
Experimental Results
Theoretical Results
Angle Of Formation (Degrees)
Column Number
90
85
80
75
70
65
60
55
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6

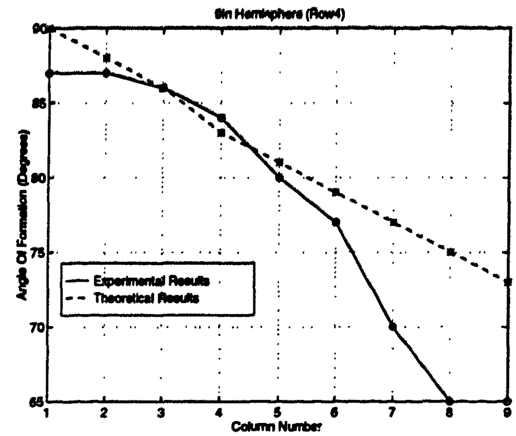

7in Hemisphere (Row 8)
Angle Of Formation (Degrees)
Column Number
90
85
80
75
70
65
60
55
1
1.5
2
2.5
3
3.5
4
4.5
5

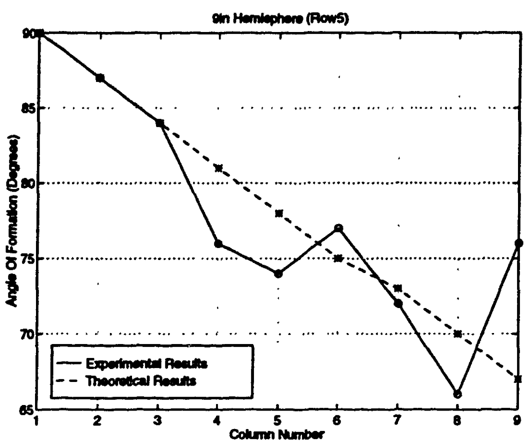

7in Hemisphere (Row 9)
Experimental Results
Theoretical Results
Angle Of Formation (Degrees)
Column Number
90
85
80
75
70
65
60
1
1.5
2
2.5
3
3.5
4

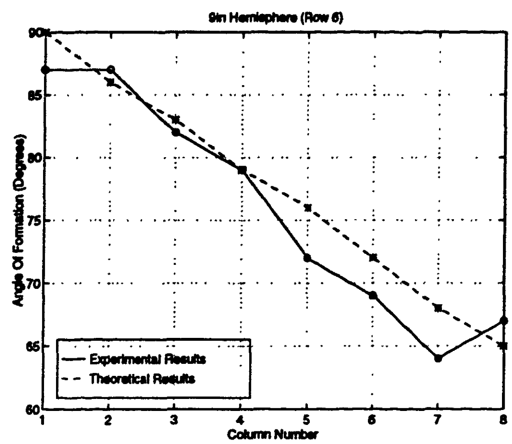

9in Hemisphere (Row 1)
Angle Of Formation (Degrees)
Column Number
Experimental Results
Theoretical Results

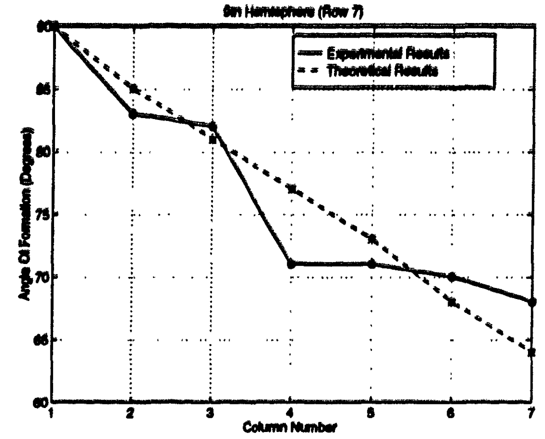

9in Hemisphere (Row 2)
Angle Of Formation (Degrees)
Column Number
Experimental Results
Theoretical Results

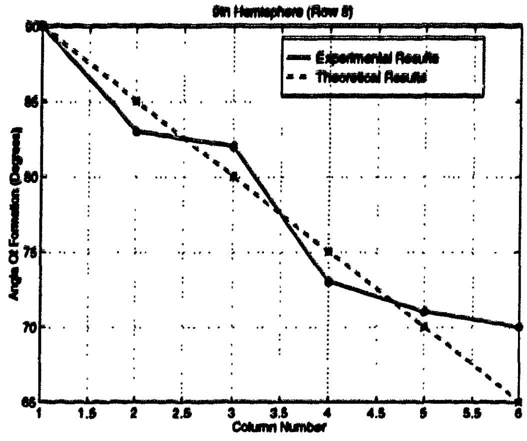

9in Hemisphere (Row 3)
Angle Of Formation (Degrees)
Column Number
Experimental Results
Theoretical Results

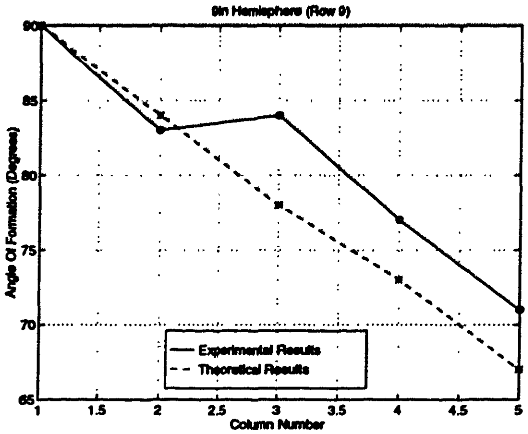

9in Hemisphere (Row4)
Angle Of Formation (Degrees)
Column Number
Experimental Results
Theoretical Results

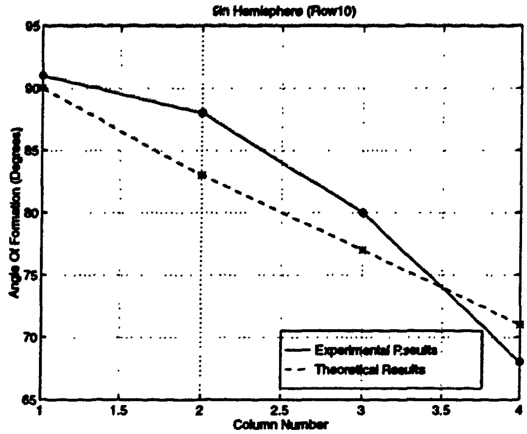

9in Hemisphere (Row5)
Angle Of Formation (Degrees)
Column Number
Experimental Results
Theoretical Results


9in Hemisphere (Row 6)
Angle Of Formation (Degrees)
Column Number
Experimental Results
Theoretical Results

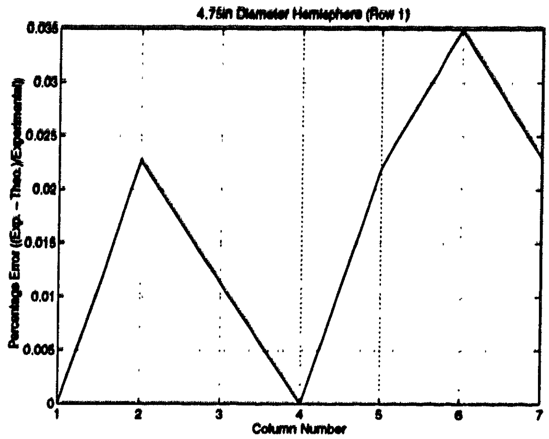

9in Hemisphere (Row 7)
Experimental Results
Theoretical Results
Angle Of Formation (Degrees)
Column Number
90
85
80
75
70
65
60
1
2
3
4
5
6
7

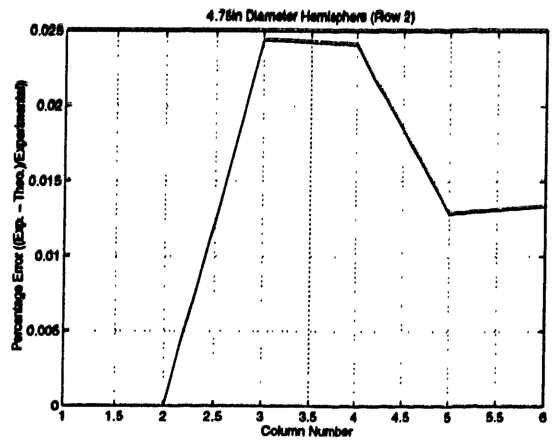

9in Hemisphere (Row 8)
Experimental Results
Theoretical Results
Angle Of Formation (Degrees)
Column Number
90
85
80
75
70
65
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6

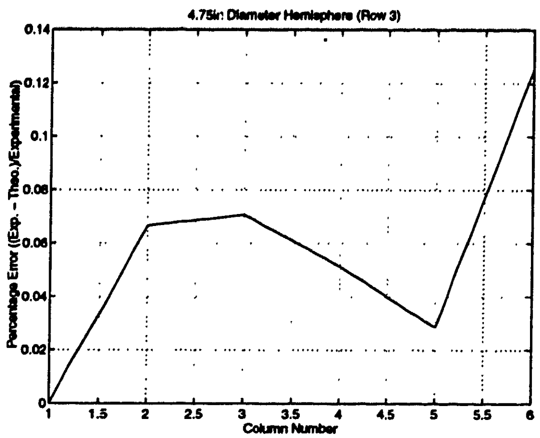

9in Hemisphere (Row 9)
Experimental Results
Theoretical Results
Angle Of Formation (Degrees)
Column Number
90
85
80
75
70
65
1
1.5
2
2.5
3
3.5
4
4.5
5

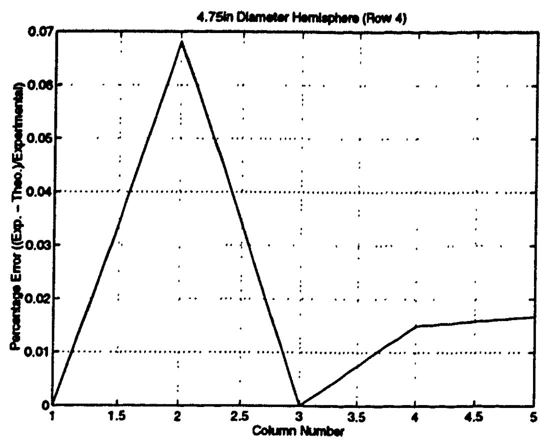

9in Hemisphere (Row10)
Experimental Results
Theoretical Results
Angle Of Formation (Degrees)
Column Number
95
90
85
80
75
70
65
1
1.5
2
2.5
3
3.5
4

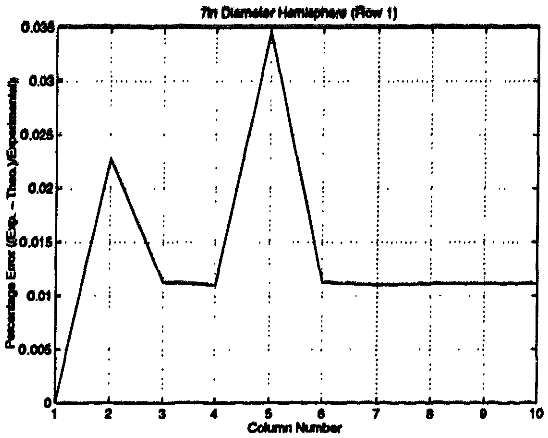
A.2 Percentage Error for Angles Measured of Each Hemisphere

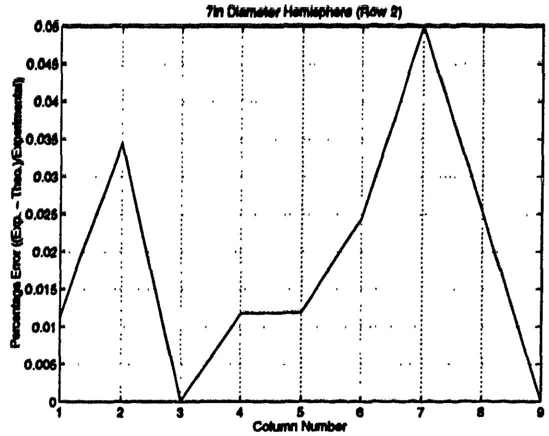


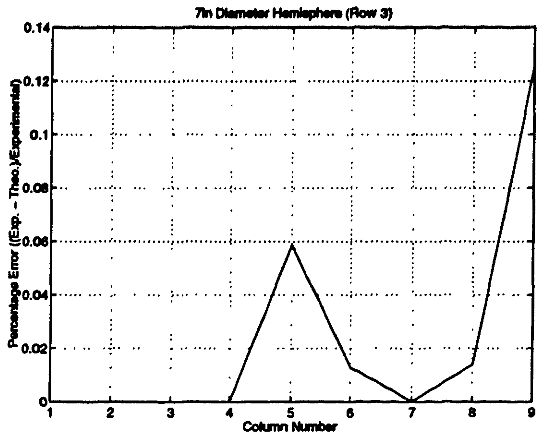


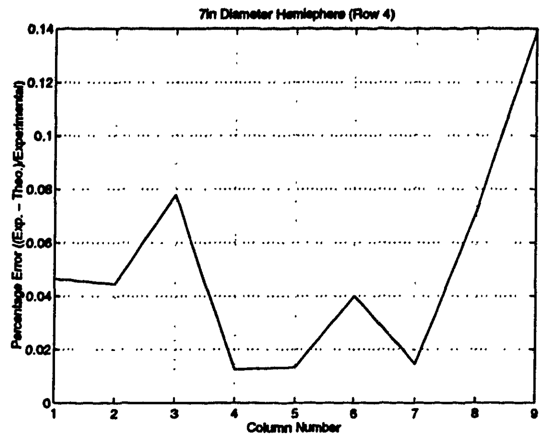


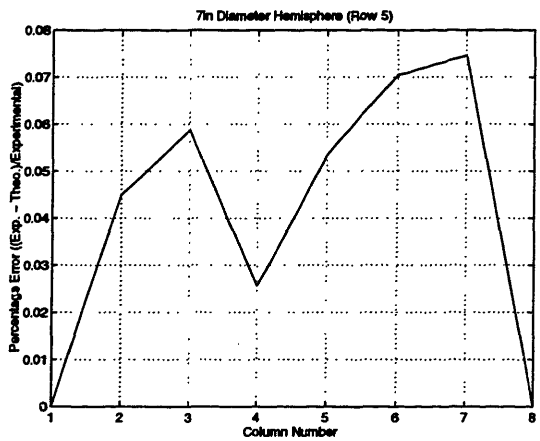


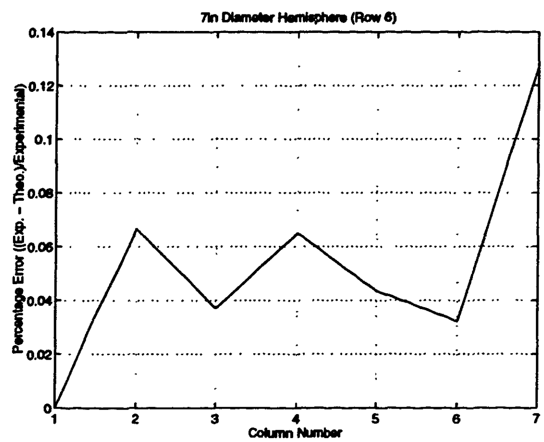

7in Diameter Hemisphere (Row 1)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
1 2 3 4 5 6 7 8 9 10

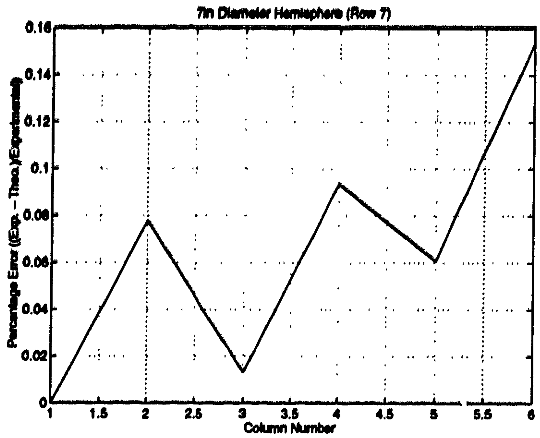

7in Diameter Hemisphere (Row 2)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
1 2 3 4 5 6 7 8 9

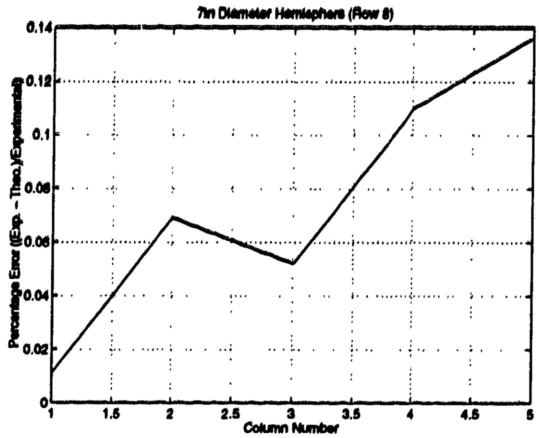

7in Diameter Hemisphere (Row 3)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1 2 3 4 5 6 7 8 9

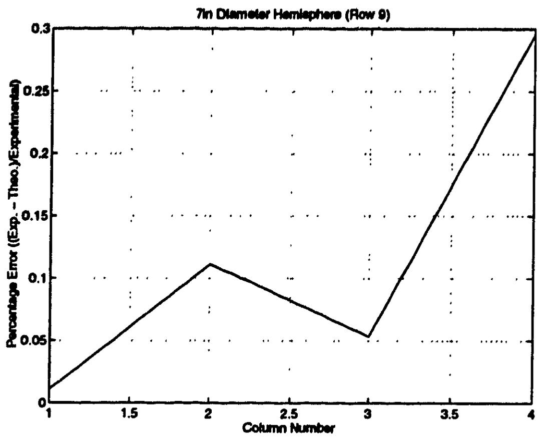

7in Diameter Hemisphere (Row 4)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1 2 3 4 5 6 7 8 9

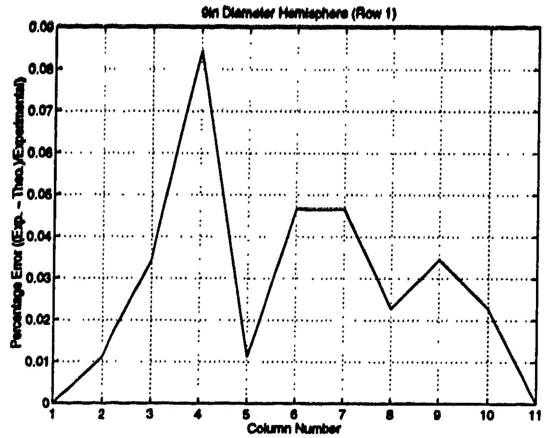

7in Diameter Hemisphere (Row 5)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8

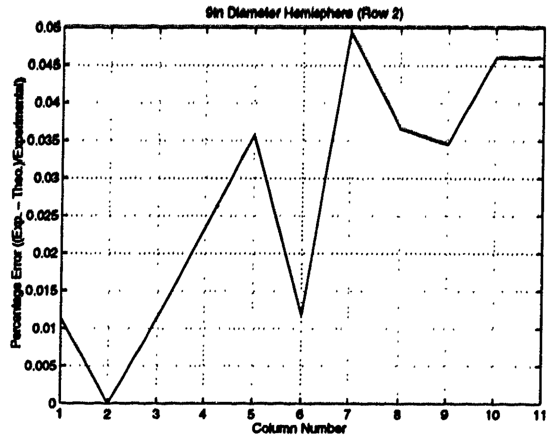

7in Diameter Hemisphere (Row 6)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1 2 3 4 5 6 7

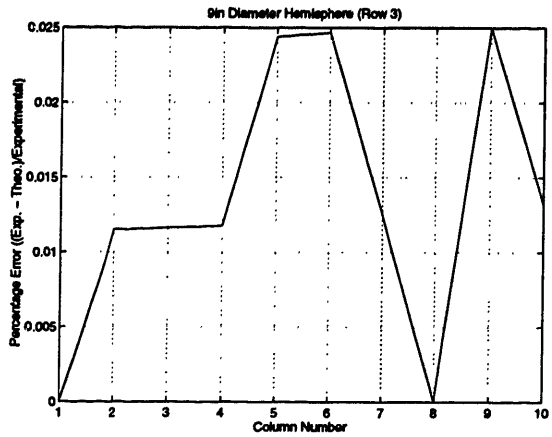

7in Diameter Hemisphere (Row 7)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

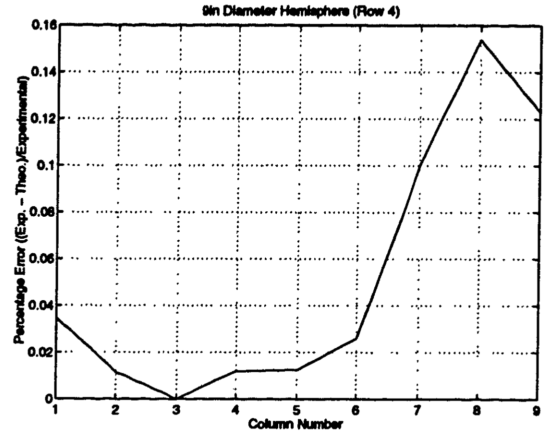

7in Diameter Hemisphere (Row 8)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

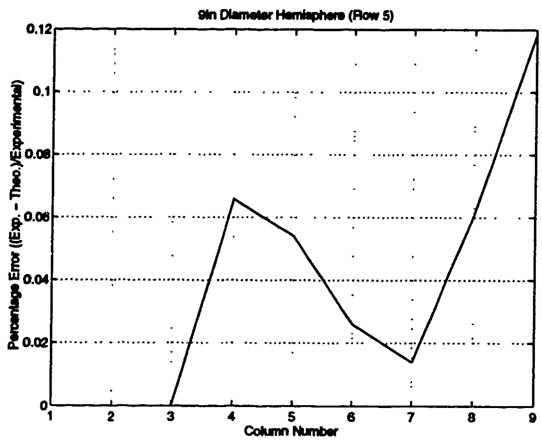

7in Diameter Hemisphere (Row 9)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

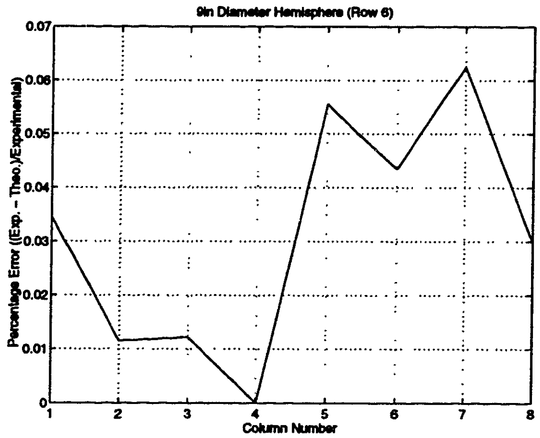

9in Diameter Hemisphere (Row 1)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

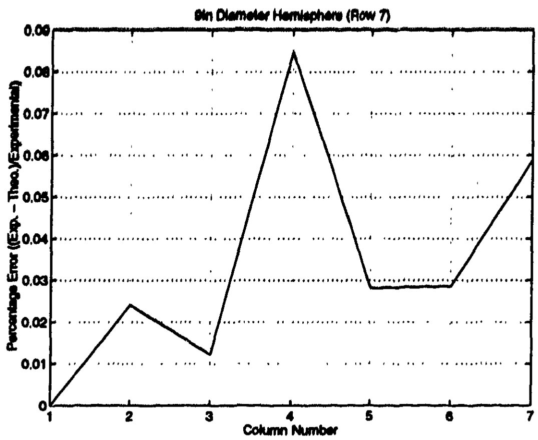

9in Diameter Hemisphere (Row 2)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

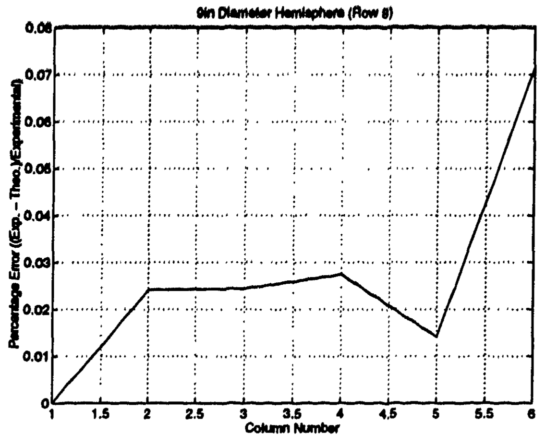

9in Diameter Hemisphere (Row 3)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

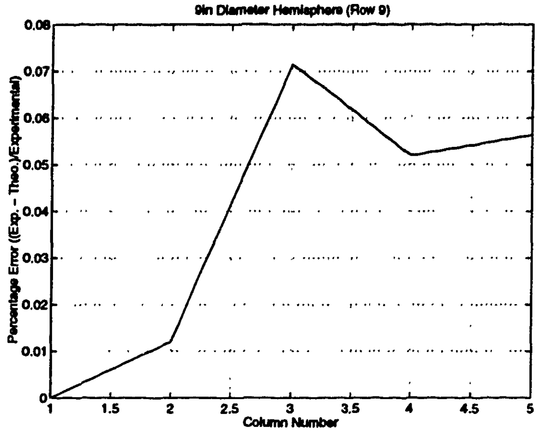

9in Diameter Hemisphere (Row 4)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

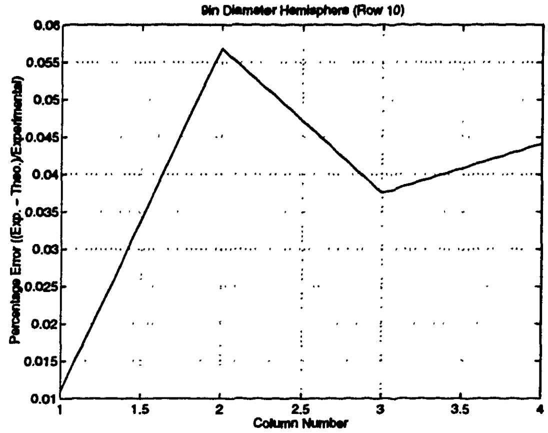

9in Diameter Hemisphere (Row 5)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number


9in Diameter Hemisphere (Row 6)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number


9in Diameter Hemisphere (Row 7)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number


9in Diameter Hemisphere (Row 8)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

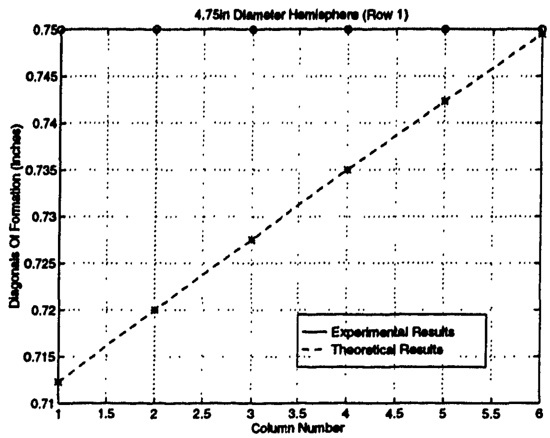

9in Diameter Hemisphere (Row 9)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

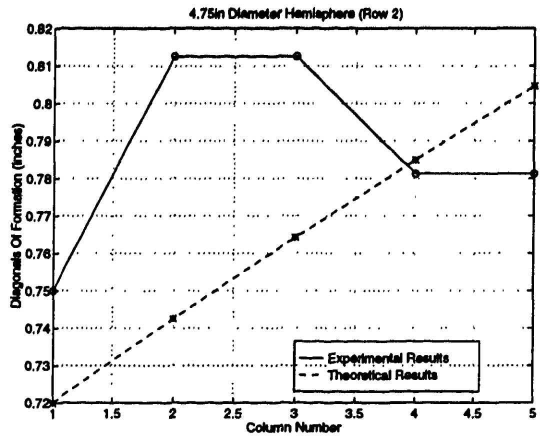

9in Diameter Hemisphere (Row 10)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

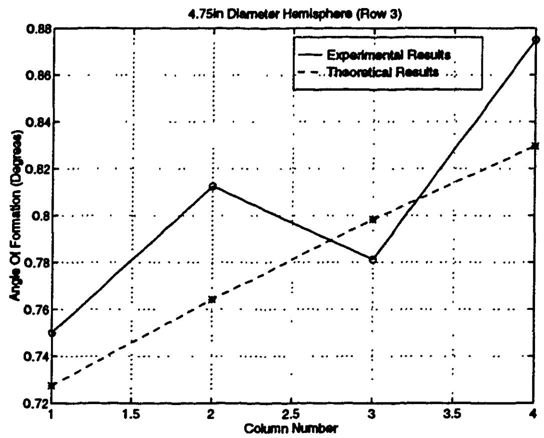
Appendix B

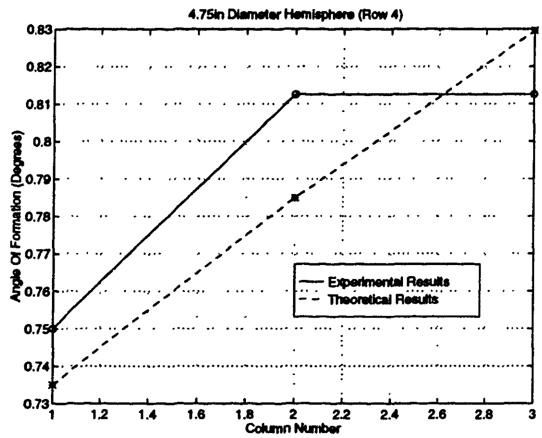
Diagonals Results of The Woven Fabric

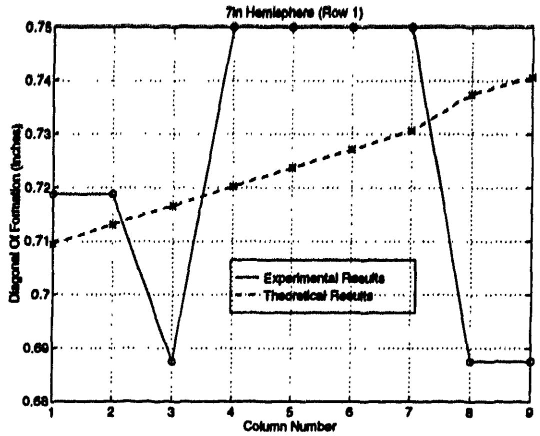
B.1 Experimental and Theoretical Diagonal Results

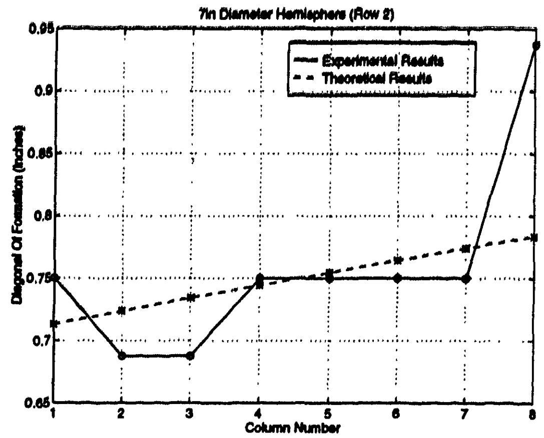


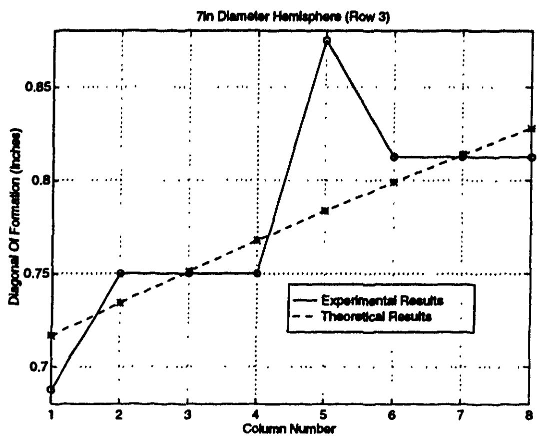


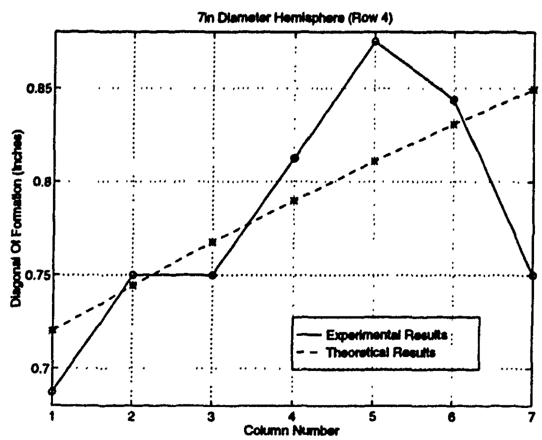


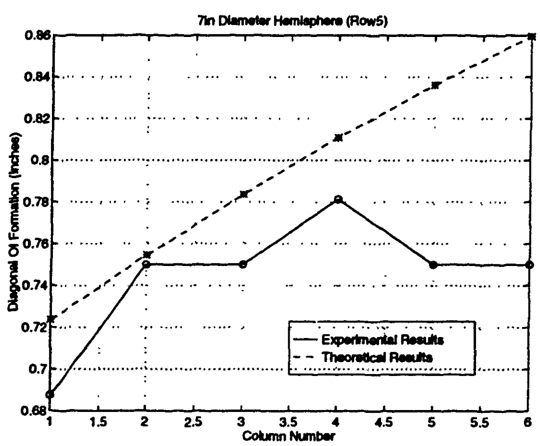


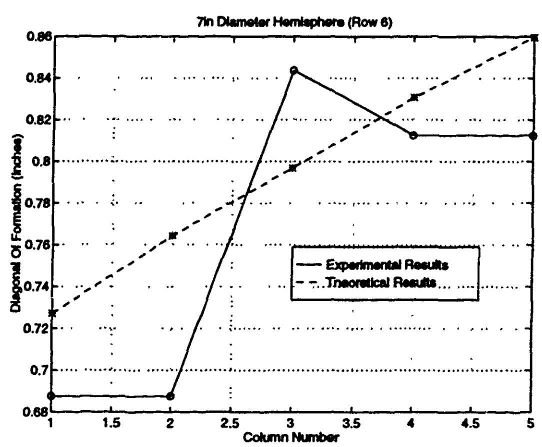

7in Hemisphere (Row 1)
Diagonal Of Formation (Inches)
Column Number
Experimental Results
Theoretical Results

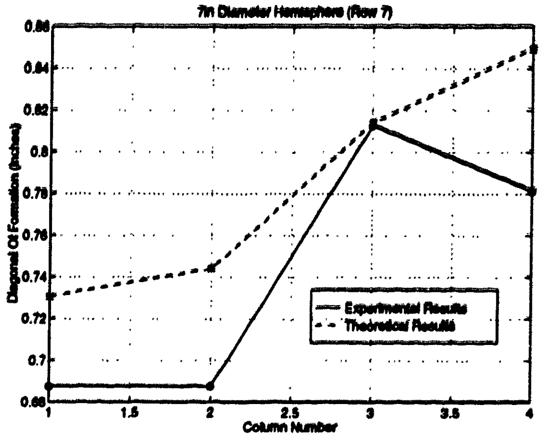

7in Diameter Hemisphere (Row 2)
Diagonal Of Formation (Inches)
Column Number
Experimental Results
Theoretical Results

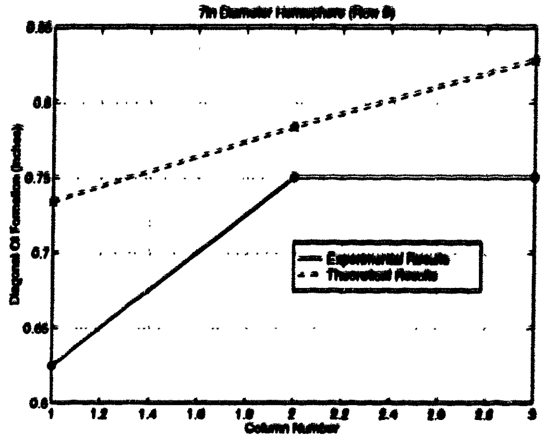

7in Diameter Hemisphere (Row 3)
Diagonal Of Formation (Inches)
Column Number
Experimental Results
Theoretical Results

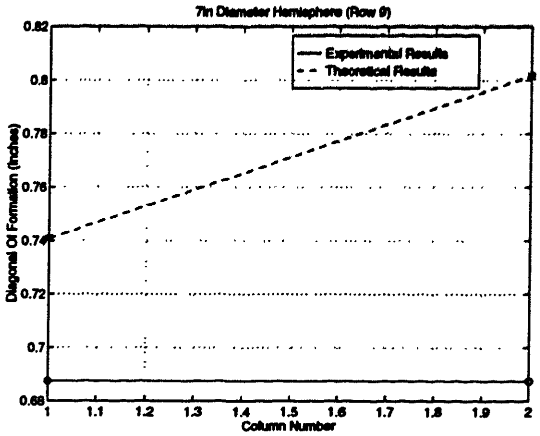

7in Diameter Hemisphere (Row 4)
Diagonal Of Formation (Inches)
Column Number
Experimental Results
Theoretical Results

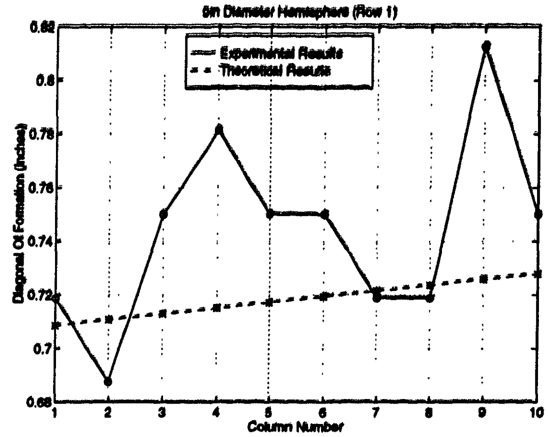

7in Diameter Hemisphere (Row5)
Diagonal Of Formation (Inches)
Column Number
Experimental Results
Theoretical Results

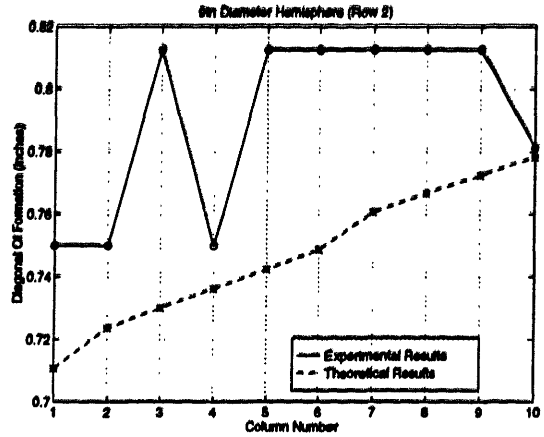

7in Diameter Hemisphere (Row 6)
Diagonal Of Formation (Inches)
Column Number
Experimental Results
Theoretical Results

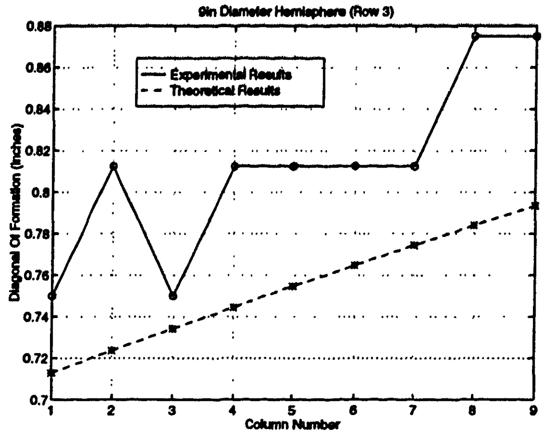

7in Diameter Hemisphere (Row 7)
Diagonal Of Formation (Inches)
Column Number
Experimental Results
Theoretical Results

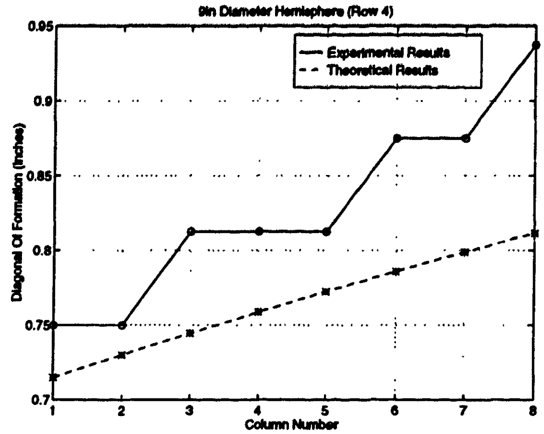

7in Diameter Hemisphere (Row 8)
Diagonal Of Formation (Inches)
Column Number
Experimental Results
Theoretical Results

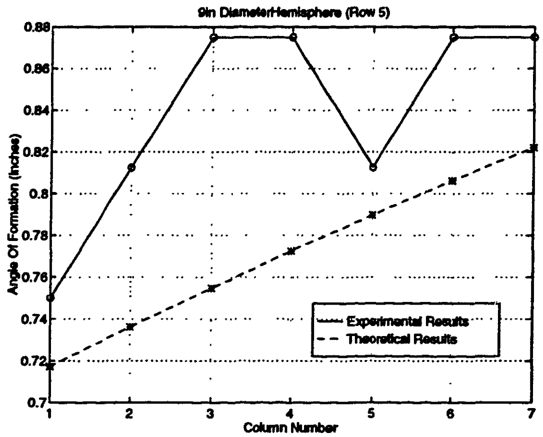

7in Diameter Hemisphere (Row 9)
Diagonal Of Formation (Inches)
Column Number
Experimental Results
Theoretical Results

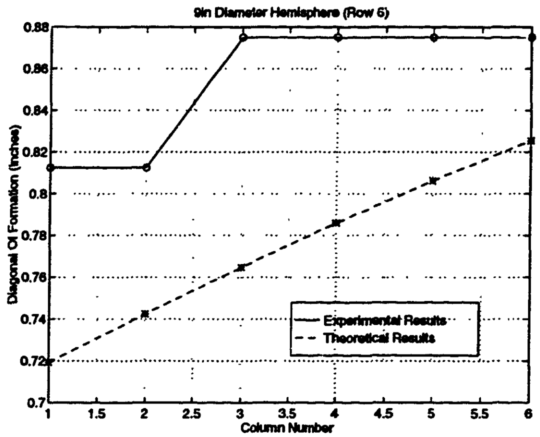

9in Diameter Hemisphere (Row 1)
Experimental Results
Theoretical Results
Diagonal Of Formation (Inches)
Column Number

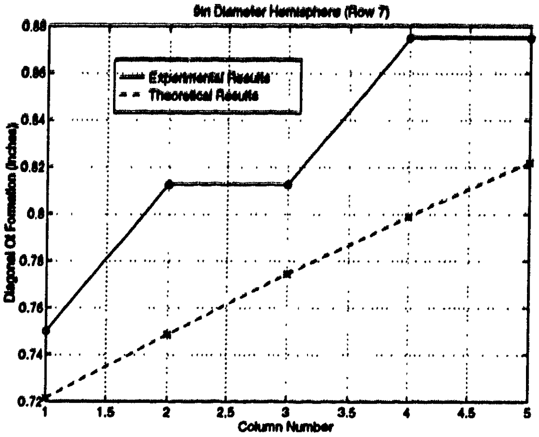

9in Diameter Hemisphere (Row 2)
Experimental Results
Theoretical Results
Diagonal Of Formation (Inches)
Column Number

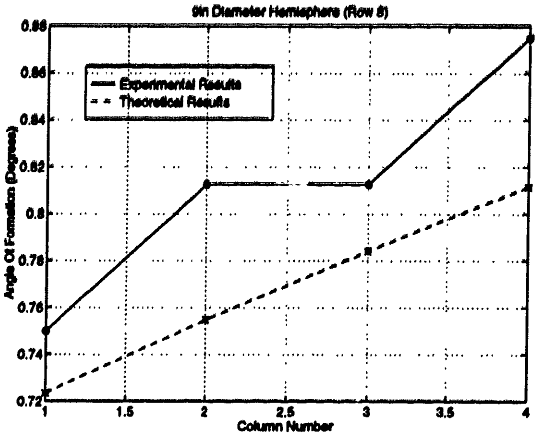

9in Diameter Hemisphere (Row 3)
Experimental Results
Theoretical Results
Diagonal Of Formation (Inches)
Column Number

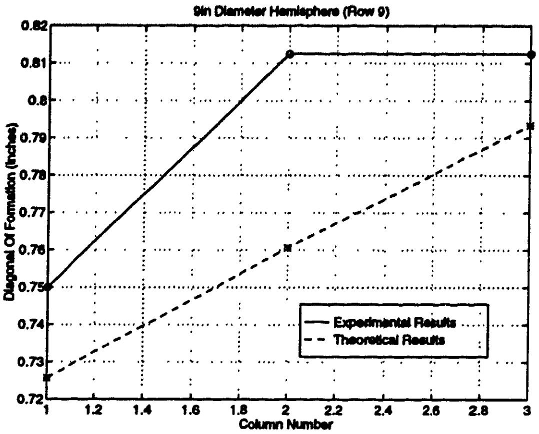

9in Diameter Hemisphere (Row 4)
Experimental Results
Theoretical Results
Diagonal Of Formation (Inches)
Column Number


9in DiameterHemisphere (Row 5)
Experimental Results
Theoretical Results
Angle Of Formation (Inches)
Column Number

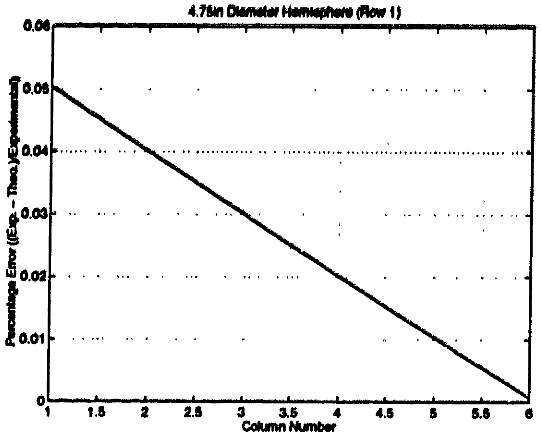

9in Diameter Hemisphere (Row 6)
Experimental Results
Theoretical Results
Diagonal Of Formation (Inches)
Column Number

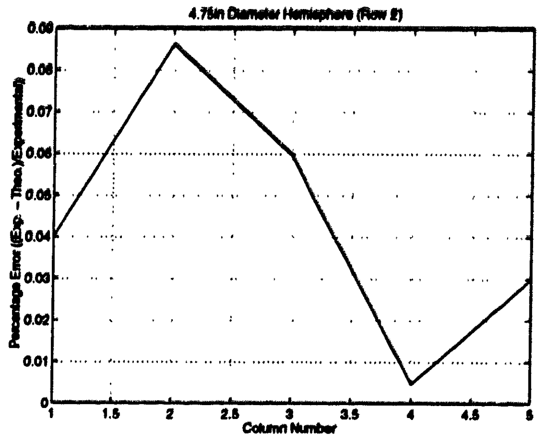

9in Diameter Hemisphere (Row 7)
Experimental Results
Theoretical Results
Diagonal Of Formation (Inches)
Column Number
0.88
0.86
0.84
0.82
0.8
0.78
0.76
0.74
0.72
1
1.5
2
2.5
3
3.5
4
4.5
5

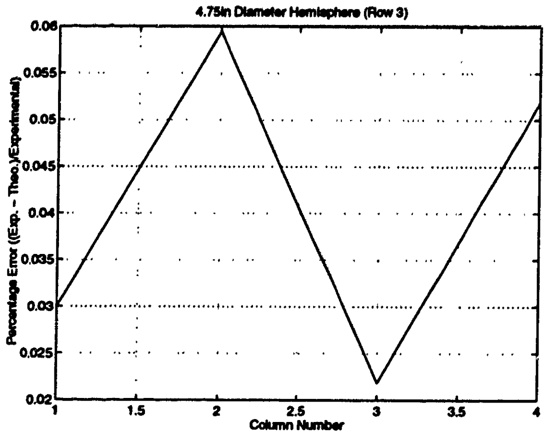

9in Diameter Hemisphere (Row 8)
Experimental Results
Theoretical Results
Angle Of Formation (Degrees)
Column Number
0.88
0.86
0.84
0.82
0.8
0.78
0.76
0.74
0.72
1
1.5
2
2.5
3
3.5
4

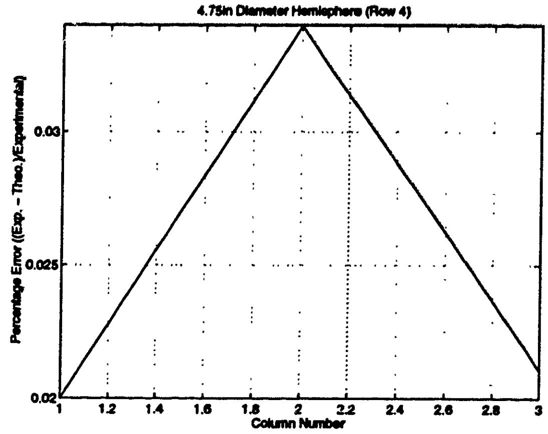

9in Diameter Hemisphere (Row 9)
Experimental Results
Theoretical Results
Diagonal Of Formation (Inches)
Column Number
0.82
0.81
0.8
0.79
0.78
0.77
0.76
0.75
0.74
0.73
0.72
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3

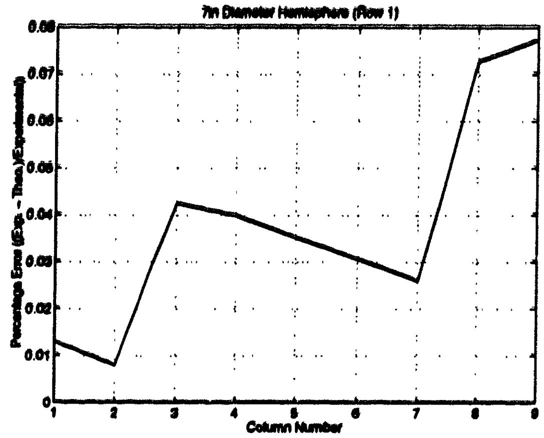
B.2 Percent Error Between Theoretical and Experimental Results

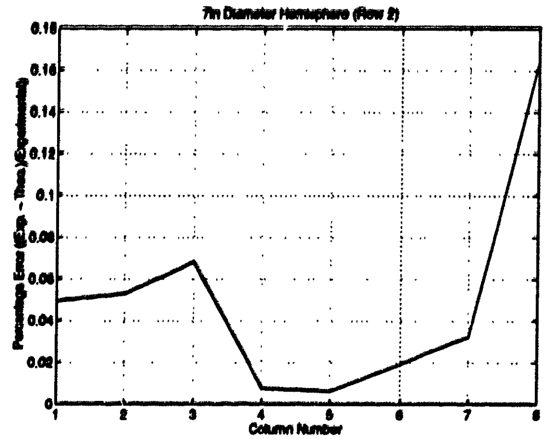


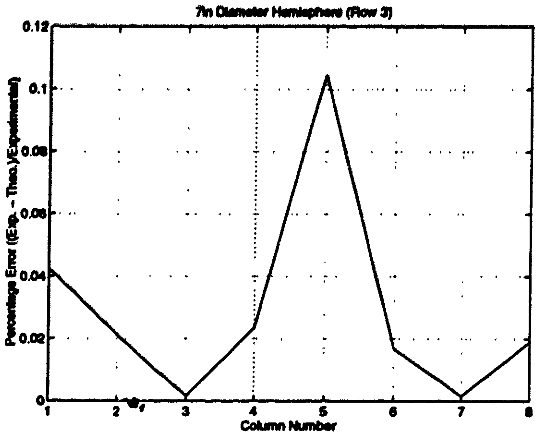


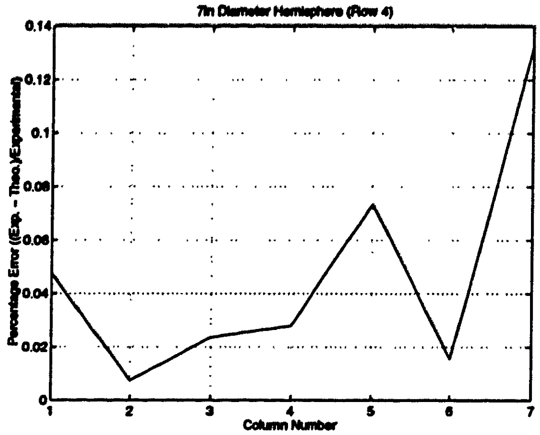


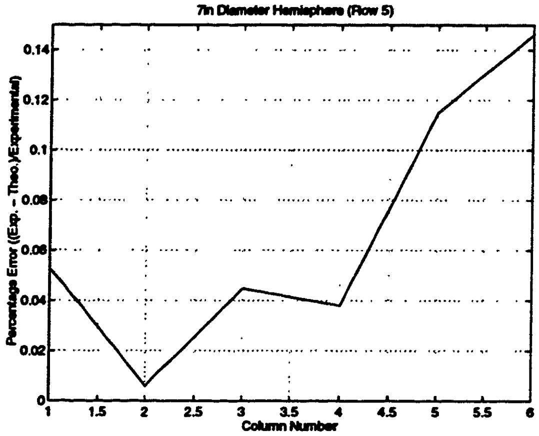


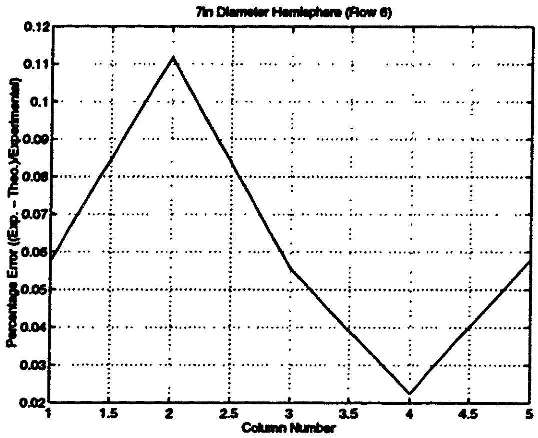

7in Diameter Hemisphere (Row 1)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

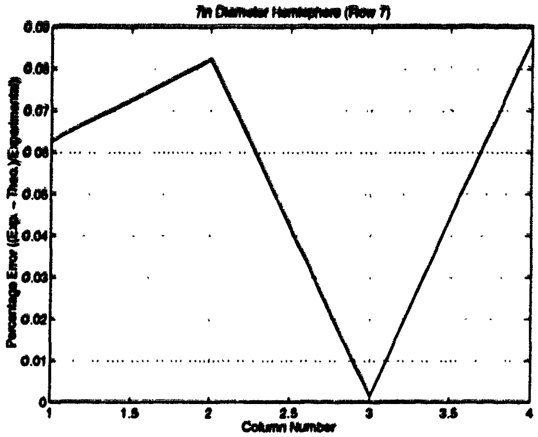

7in Diameter Hemisphere (Row 2)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

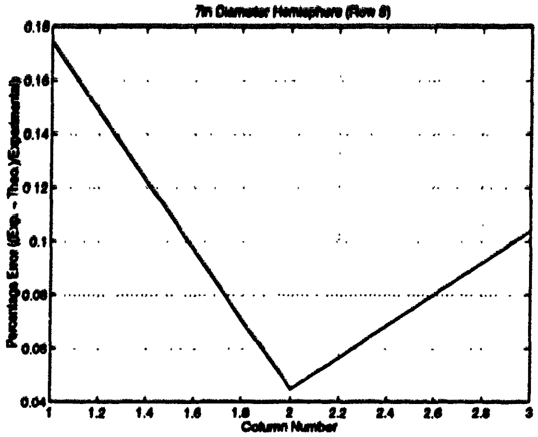

7in Diameter Hemisphere (Row 3)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

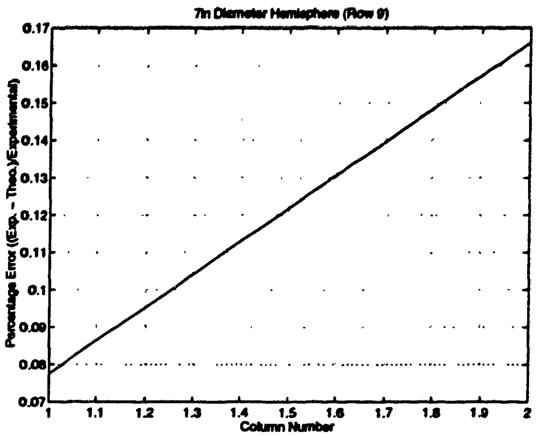

7in Diameter Hemisphere (Row 4)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

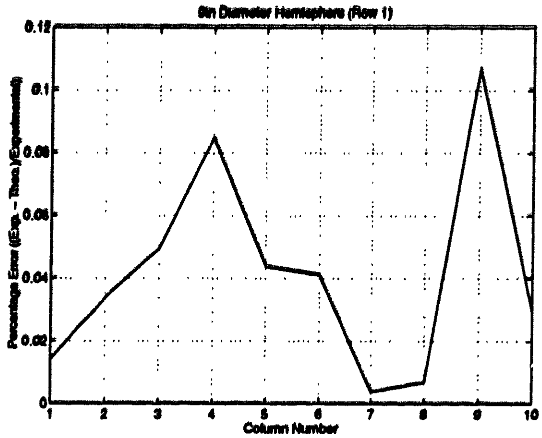

7in Diameter Hemisphere (Row 5)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

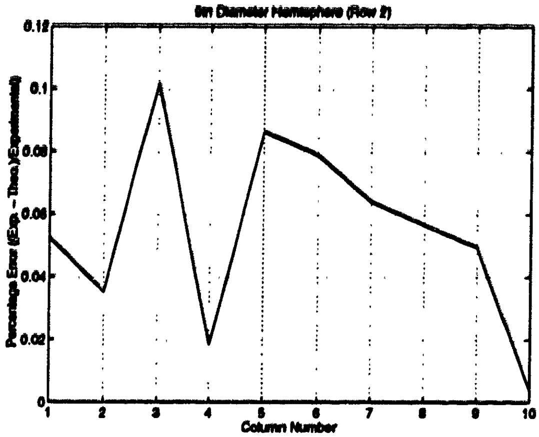

7in Diameter Hemisphere (Row 6)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number


7in Diameter Hemisphere (Row 7)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number


7in Diameter Hemisphere (Row 8)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number


7in Diameter Hemisphere (Row 9)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number


9in Diameter Hemisphere (Row 1)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number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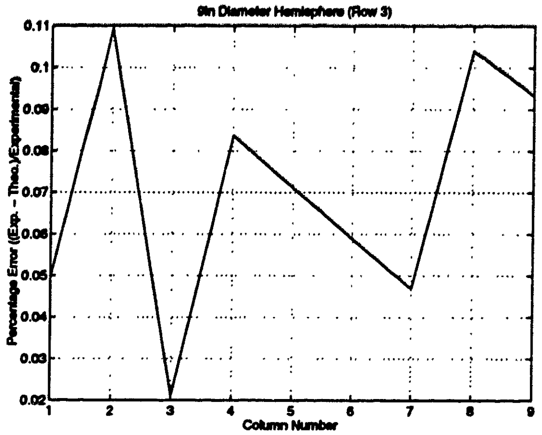
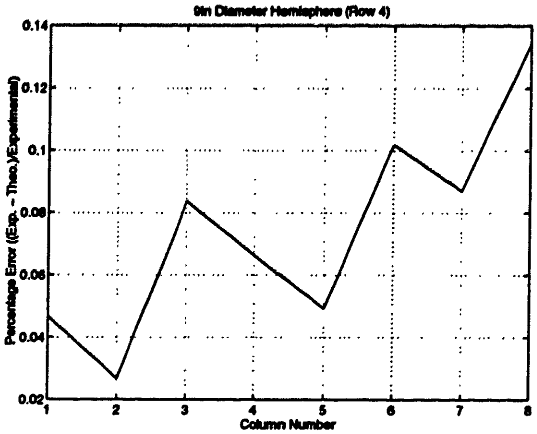
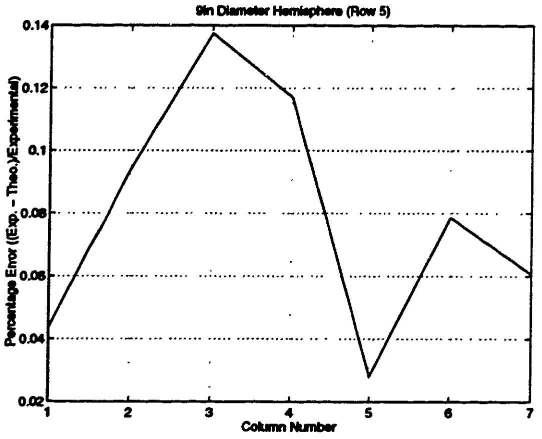
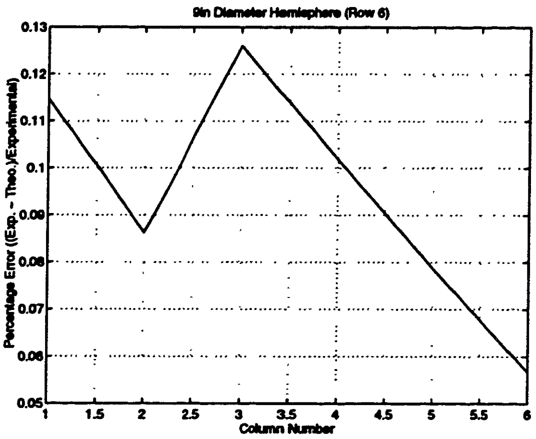
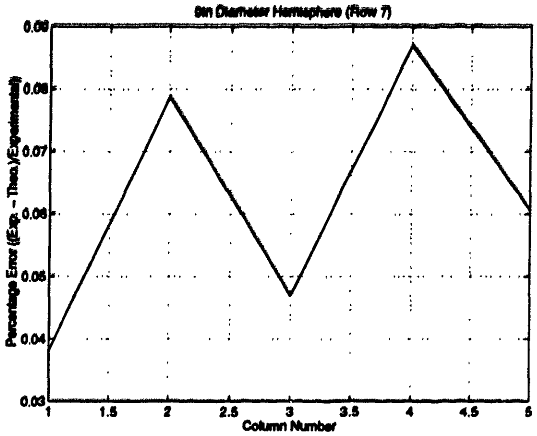
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

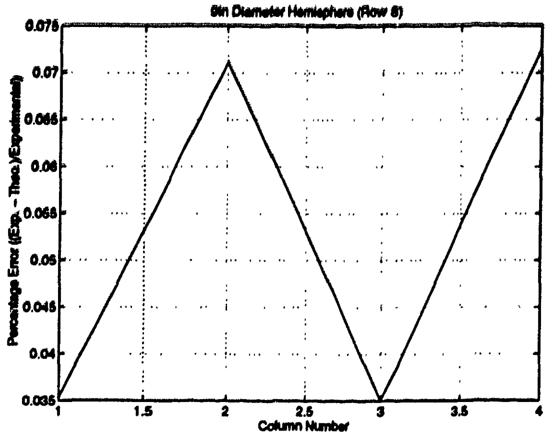

9in Diameter Hemisphere (Row 3)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

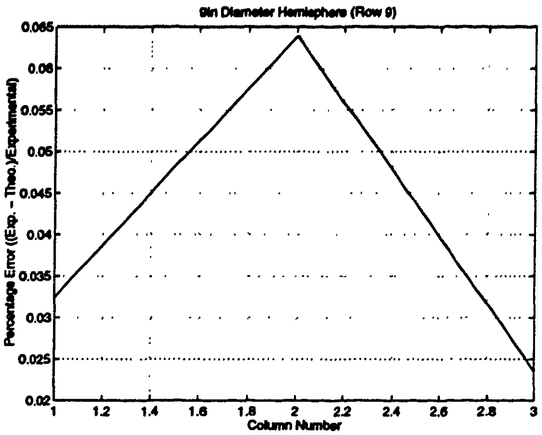

9in Diameter Hemisphere (Row 4)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

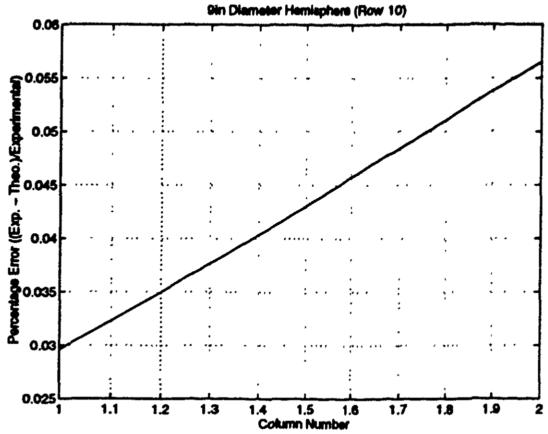

9in Diameter Hemisphere (Row 5)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number


9in Diameter Hemisphere (Row 6)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number


9in Diameter Hemisphere (Row 7)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number


9in Diameter Hemisphere (Row 8)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number


9in Diameter Hemisphere (Row 9)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number


9in Diameter Hemisphere (Row 10)
Percentage Error ((Exp. - Theo.)/Experimental)
Column Number

Appendix C

Tabulated Averages and Standard Devs. of Angles

Percent Average and Standard Deviations of Angles												
	4.75in Diameter	0	0.0227	0.0112	0	0.022	0.0349	0.323				
		0	0	0.3244	0.0242	0.0128	0.0133					
		0	0.0667	0.0706	0.0513	0.0286	0.125					
		0	0.0682	0	0.0149	0.0167						
		0	0.1576	0.1062	0.0903	0.0801	0.1732	0.023	0.026266667			
	Percent Average:	0.026266667										
	Standard Deviation:	0.029923634										
	7in Diameter	0	0.0227	0.0112	0.011	0.0345	0.0122	0.011	0.0111	0.0111	0.0111	
		0.0112	0.0345	0	0.0118	0.0119	0.0224	0.05	0.0253	0		
		0	0	0	0	0.0588	0.013	0	0.0139	0.125		
		0.465	0.0444	0.0778	0.0125	0.0133	0.04	0.3145	0.0714	0.1389		
		0	0.0449	0.0588	0.0256	0.0533	0.0704	0.0746	0			
		0	0.0667	0.037	0.0649	0.0435	0.0323	0.127				
		0	0.0778	0.0132	0.0933	0.0606	0.1538					
		0.0111	0.069	0.0519	0.1096	0.1364						
		0.0111	0.0111	0.0533	0.2955							
	Percent Average:	0.048316418										
	Standard Deviation:	0.07082203										
	9in Diameter	0	0.0112	0.0345	0.0843	0.0112	0.0465	0.0465	0.0227	0.0345	0.0227	[illegible]
		0.0112	0	0.0115	0.0233	0.0357	0.0118	0.0494	0.0366	0.0345	0.046	0.345
		0	0.0115	0.0116	0.0118	0.0244	0.0247	0.0125	0	0.025	0.0132	
		0.0345	0.0115	0	0.0119	0.0125	0.028	0.1	0.1538	0.1231		
		0	0	0	0.0658	0.0541	0.028	0.0139	0.0606	0.1184		
		0.0345	0.0115	0.0122	0	0.0556	0.0435	0.0625	0.0299			
		0	0.0241	0.0122	0.0845	0.0282	0.0286	0.0588				
		0	0.0241	0.0244	0.0274	0.0741	0.0714					
		0	0.012	0.0714	0.0519	0.0563						
		0.011	0.0568	0.0375	0.0441							
	Percent Average:	0.032366667										
	Standard Deviation:	0.03092546										

Appendix D

Tabulated Averages and Standard Devs. of Diagonals

Percent Averages and Standard Deviations of Diagonals											
	4.75in Diameter	0.0503	0.04	0.03	0.02	0.0103	0.0007				
		0.04	0.0862	0.0594	0.0047	0.0229					
		0.03	0.0594	0.0218	0.0519						
		0.02	0.034	0.021							
	Percent Average:	0.033477778									
	Standard Deviation:	0.021164004									
	7in Diameter	0.0129	0.0079	0.0423	0.0397	0.0351	0.0305	0.0259	0.0726	0.0772	
		0.0492	0.0527	0.0679	0.0075	0.006	0.0191	0.032	0.1643		
		0.0423	0.0211	0.0016	0.0236	0.1045	0.0167	0.0015	0.019		
		0.0476	0.075	0.0236	0.0279	0.0733	0.0155	0.1325			
		0.0527	0.006	0.0448	0.038	0.1149	0.1461				
		0.0576	0.117	0.0555	0.0224	0.058					
		0.0627	0.0822	0.0015	0.0872						
		0.1744	0.0447	0.1039							
		0.0775	0.1661								
	Percent Average:	0.055417308									
	Standard Deviation:	0.04447564									
	9in Diameter										
		0.0141	0.0337	0.0495	0.0848	0.0437	0.0409	0.0037	0.0067	0.1068	0.0295
		0.0524	0.0352	0.1015	0.0184	0.0863	0.0786	0.0639	0.0565	0.0494	0.0039
		0.0495	0.1094	0.0211	0.0837	0.0711	0.0588	0.0469	0.104	0.0933	
		0.0467	0.0267	0.0837	0.0662	0.0492	0.1018	0.087	0.1344		
		0.0437	0.0939	0.1375	0.1171	0.0281	0.0786	0.0606			
		0.1147	0.0863	0.1261	0.1018	0.0786	0.0567				
		0.0381	0.0786	0.0469	0.087	0.0606					
		0.0353	0.0711	0.0351	0.0726						
		0.0324	0.0639	0.0235							
		0.0296	0.0565								
	Percent Average:	0.06325									
	Standard Deviation:	0.032481047									

References

[1] H. Li, G. Dillon, S. Chey, and T.G. Gutowski. "A Kinematic Approach For Diaphragm Forming of Advanced Composites", Proceedings of the 40th SAMPE International Symposium (1995).

[2] F. Van Der Weeen. "Algorithms For Draping Fabrics On Doubly-Curved Surfaces", International Journal For Numerical Methods In Engineering, Vol. 31, 1415-1426 (1991).

[3] T.G. Gutowski, D. Hoult, G. Dillon, and J. Gonzalez-Zugasti. "Differential Geometry and the Forming of Aligned Fibre Composites", Composites Manufacturing, 2, (3/4), 147-152 (1991).

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