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Stress concentrations around an axisymmetrically attached nozzle on a glass reinforced plastic hemispherical dome

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2.6 BRIEF DESCRIPTION OF THE COMPUTER MODELS

Data Processing

Lamination Theory

BIGFOOT is based on the lamination theory mathematical model. It is capable of processing various material layer properties and fibre directions. It is initialised using either midplane strain or surface strain input which results in the determination of the stresses, forces, curvatures, moments and strains. All data obtained may then be stored on file and retrieved for either tabulation purposes or graphical purposes.

Graphics

BIGPLOT has been developed with the spline curve plotting procedure as its core. Data can either be inputted or retrieved from data files and then plotted in various configurations. Using the data retrieval process results of the lamination theory analysis may be graphically interpretted with the minimum of roundoff errors being induced.

Stress Models: (Isotropic)

I thought it imperative that despite the analysis of the hemisphere being one of a research nature that the information resulting from the work should be of value in engineering design.

No personal computer programs were readily available for analysing the stress distribution of a nozzle and hemisphere configuration, particularly that constructed of an anisotropic material. The analysis of these materials requires extensive computer hardware backup together with complex finite element programming techniques.

These factors contributed to the consideration of using isotropic mathematical theory for developing the computer programs. These would be used to predict the stress behaviour around the stress compensation region at a nozzle attachment site. A factor which further supported using isotropic theory was that the stress level to which the hemisphere was taken under an internal pressure was minimal ie. only 5% of the materials failure stress. Thus it was assumed that the anisotropic material would behave isotropically at this "low" stress level.

Two computer models were considered for this purpose. The first model considers the nozzle to be a flat plate on a hemispherical shell of varying wall thickness. The second method for prediction utilises a matrix system for solving a set of simultaneous equations according to a given set of boundary conditions. These conditions were ones which closely resembled the hemisphere/nozzle configuration, when under an internal pressure load.

A more detailed description of both programs is to follow in which their method of operation and data input details are given.

Thin Walled, First Principles Truncated Elements

This model has been developed from the theory provided in :

ASME, "Boiler and Pressure Vessel Code", 1968,
Section viii - Division 2, Pressure Vessel Article 4 - 3,
"Analysis of Spherical Shells".

A copy of this article is found in Appendix F.

Figure 4 shows the two components of the hemisphere/nozzle configuration used for approximating the stresses in the overlay laminate.

i) The nozzle is considered as an annular plate with a fixed outer edge and a guided centre. The plate has a distributed load applied to its surface. Table 24 No. 25 of Roark (1983) provides the formula for calulating the edge moment for this load situation.

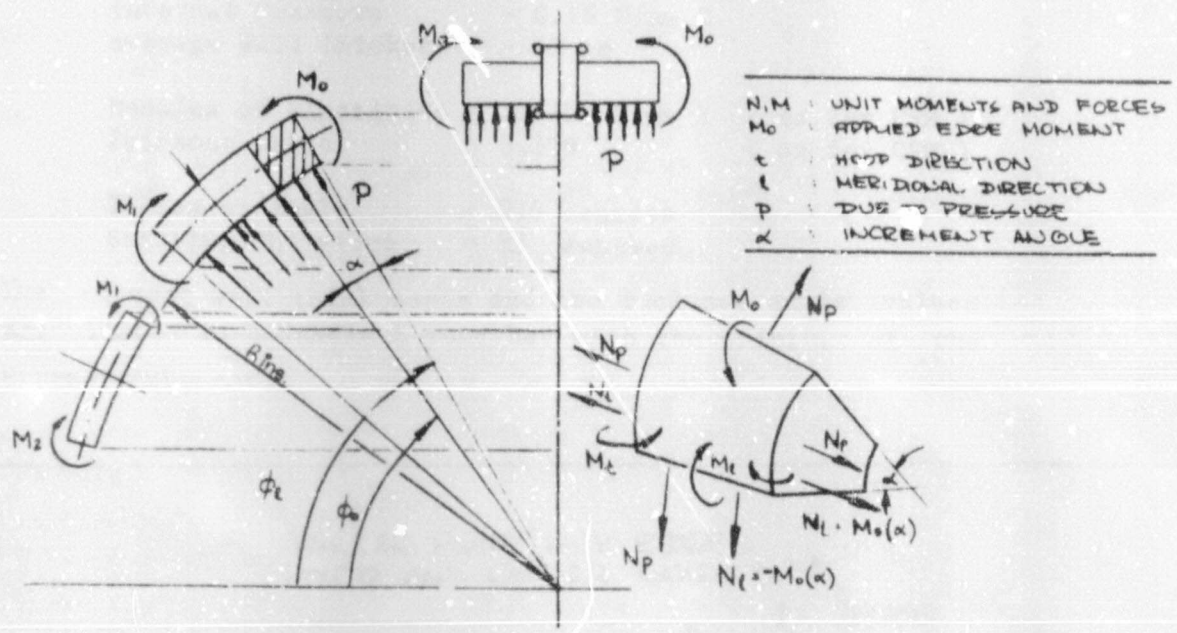


Figure 4. Elements of the first principles computer model

ii) The overlay and the hemisphere are modelled as being truncated elements of various thicknesses. The theory used in the analysis of the stress distribution on these elements considers the stress incurred by an applied edge moment and an internal pressure. The resulting plane and bending stresses provide the approximate total stress found within the element.

Flow Diagram - In figure 11, Appendix G, a flow diagram is provided which is accompanied by directions for operating the computer program.

Preparation and Test procedure

Running the Program - Figure 5 indicates the dimensions used for each element of the hemispherical wall and the nozzle overlay.

The data used in running the program was as follows:

Hemisphere Diameter	- 1054 mm	
Nozzle Cut-out Diameter	- 100 mm	
Internal Pressure	- 0.16 N/mm 2.	
Average Wall Thickness	- 12 mm	
Modulus of Elasticity	- 10 300 N/mm 2	(as for CSM)
Poissons Ratio	- 0.339	(as for CSM)
Increment Angle	- 0.2 degrees	
Starting Phi value	- 85 degrees	

The element wall thicknesses and the included angle values are listed in Appendix E together with the printout of the stress components.

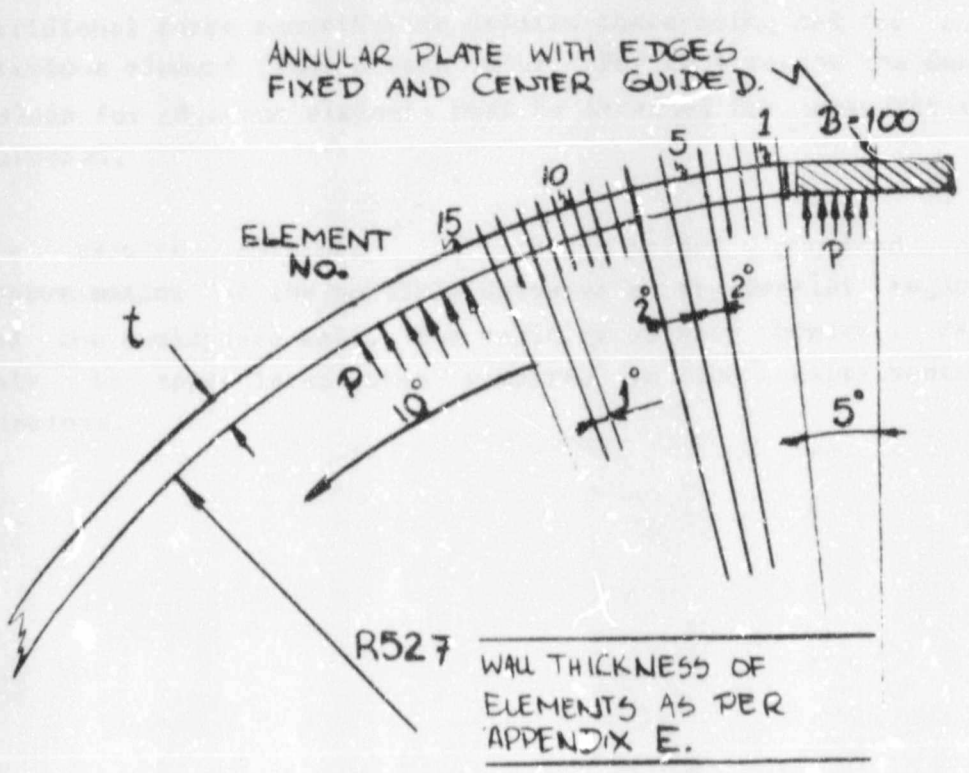


Figure 5. Element dimensions for the first principles computer model.

As this was a first approximation model, the hemispherical wall was considered to have a constant wall thickness of 8 mm, the same as the design wall thickness value. Following the post-test analysis it was found that the wall thickness varied from 7 to 8 mm.

The thickness variation of the overlay region however, was considered in the choice of element dimensions and thus the values were similar to those of the actual test rig.

It is noticed that the chopped strand mats Modulus of Elasticity and Poissons Ratio values were used. The reason being that the hemispheres material of construction consisted mainly of CSM ie approximately 80% by weight.

In analysing equations 1 to 6 section 4-330 of Appendix F, it will be seen that for alpha equal to zero, the meridional unit force will be zero. This means that for each new element considered the initial stress values will have no unit meridional force contribution despite there being one for the previous element final stress value. For this reason the mean values for adjacent elements must be obtained for comparative purposes.

The results obtained from this method provided an approximation of the possible stresses in the overlay region and the hemisphere wall. The validity of this however, can only be appreciated when compared to the experimental findings.

Thin Walled Simplified Finite Element Method

This program has been adapted from a program described in Ross (1984). The program listing is provided in Appendix 5 of his book.

It covers the stress analysis of axisymmetrical thin-walled structures of varying thickness when under a given internal pressure.

The elements which are used in the analysis can be more clearly seen in figure 6. Here the elements are tapered with constant meridional curvature. There are two nodal circles at the ends of a truncated shell element.

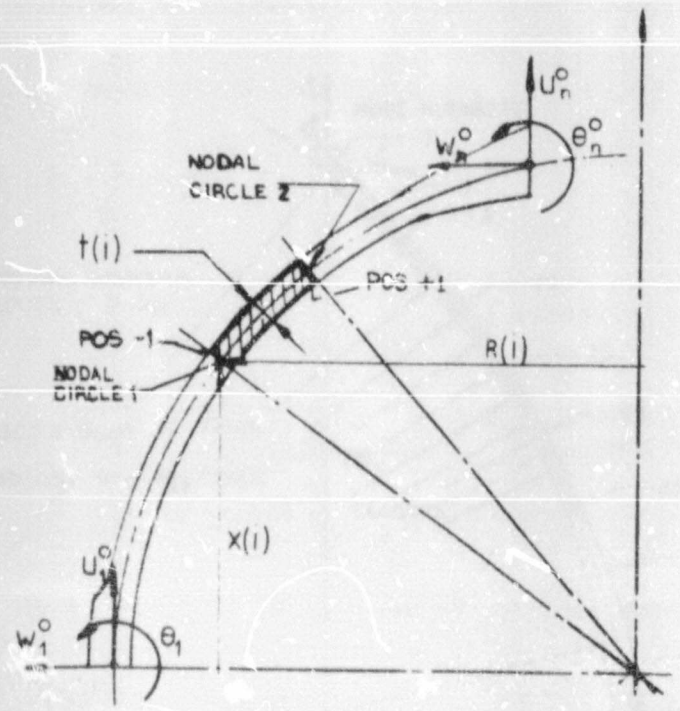


Figure 6. Principle element and relevant variables for the FEM computer model.

The program is versatile in having consideration for elements with varying meridional radius, (positive or negative). Each

element has three degrees of freedom per nodal circle (U_i°, W_i° and θ_i°) making a total of six degrees of freedom per element.

The stresses in the meridional and the hoop directions may be obtained on the inside and the outside surface of each element. These occur along both nodal circles for a given set of boundary conditions.

Flow Diagram - In figure 12, Appendix G, a flow diagram is provided which is accompanied by directions for operating the computer program.

Running the Program - Figure 7 indicates the positions of the nodes on the hemisphere together with the boundary condition specified for nodes 1 and 43.

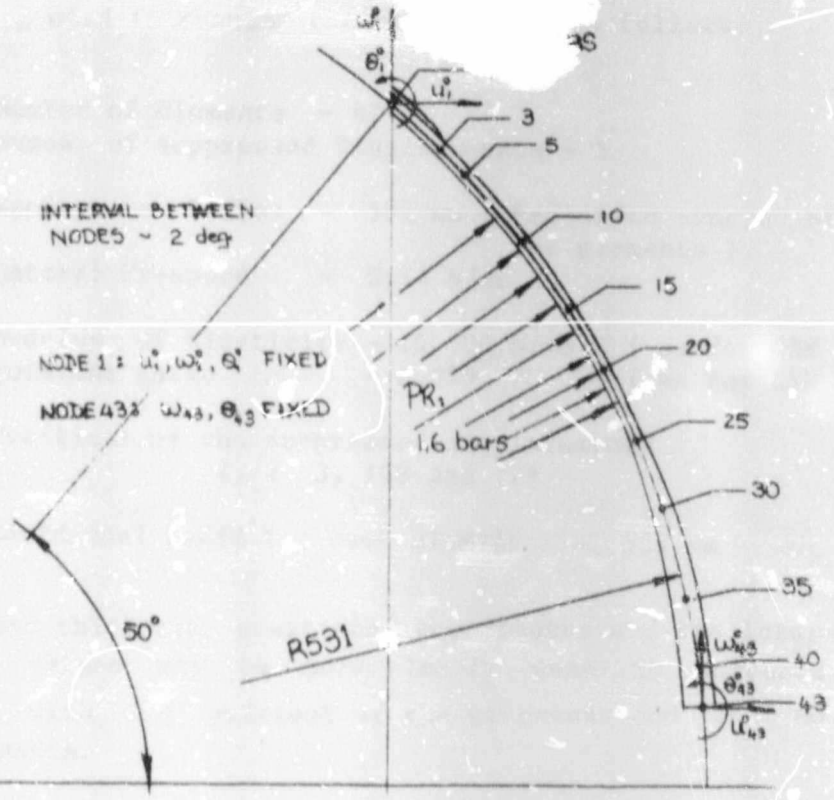


Figure 7. Elements and displacement directions for the FEM computer model.

Due to a limitation on the size of a matrix possible on a Personal Computer it was required that the hemisphere be reconfigured to provide a more manageable matrix. Therefore, the hemisphere base flange was moved from nodal circle 531 mm radius to nodal circle 406.77 mm radius. These changes had a partial effect on the wall stresses and no effect on the stress distribution of the overlay region. This dimensional change of the hemisphere provided the capability of utilising 42 shell elements for stress analysis.

The boundary conditions considered

i) The hemisphere base flange to be suppressed in the axial, radial and the theta directions. (fixed)
ii) The nozzle junction is assumed to be suppressed in the radial and the theta directions. (clamped)

The data used in running the program was as follows:

Number of Elements - 42
Number of suppressed Displacements - 5

Hemisphere Radius - 531 mm (Radius to centre of the elements)
Lateral Pressure - 0.16 N/mm 2.

Modulus of Elasticity - 10 300 N/mm 2 (as for CSM)
Poissons Ratio - 0.339 (as for CSM)

Positions of the suppressed displacements
1, 2, 3, 128 and 129

Meridional Radii for each element - 531 mm

The element thickness, positional coordinates and the lateral pressure values may be more clearly seen in Appendix E together with the printout of the stresses and the nodal displacements.

The use of these data values meant that the relevant element was chosen which corresponded to the strain gauge station position on the hemisphere. This provided the means for the graphical comparisons described in the next section.

3.0 RESULTS AND OBSERVATIONS

Brief Summary of Lamination Theory Equations

Stress:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} = [Q] \begin{Bmatrix} \epsilon_x^o \\ \epsilon_y^o \\ \gamma_{xy}^o \end{Bmatrix} + [Z] \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix}$$

Force:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} = [A] \begin{Bmatrix} \epsilon_x^o \\ \epsilon_y^o \\ \gamma_{xy}^o \end{Bmatrix} + [B] \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix}$$

Moments:

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = [B] \begin{Bmatrix} \epsilon_x^o \\ \epsilon_y^o \\ \gamma_{xy}^o \end{Bmatrix} + [D] \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix}$$

σ : laminate stress - MPa
N : force resultant - force per unit length
M : moment resultant - moment per unit length
[Q] : transformed reduced stiffness matrix
[A] : extensional stiffness matrix
[B] : coupling stiffness matrix
[D] : bending stiffness matrix
ϵ^o : midplane strain
k : laminate curvature
x, y, xy: subscripts indicating directions of analysis relative to the principal axes.

From the equations it is apparent that the stresses, forces and moments are directly proportional to the *laminate properties* and to the *strains* and *curvatures*

The observations have therefore been laid out in the following manner:

- Analysis of each of the laminate elements of the strain gauge stations
- Investigation of the midplane strain and curvature curves
- Checking the trends of the force and moment curves
- Interpretation of the inside and outside stress curves in the hoop and the meridional directions
- Observations of the contribution of the plane and bending stress components to the total wall stress at 1.6 bars
- Comparisons of the isotropic and experimental results at a pressure of 1.6 bars

3.1 DIMENSIONAL AND PROPERTY CHARACTERISTICS OF THE STRAIN GAUGE LAMINATE ELEMENTS

Table 3 provides a tabulated listing of the contents of each laminate element together with layer thicknesses and the total wall thicknesses.

The strain gauge stations are placed on three arms, at 120 degree intervals around the hemisphere, as is indicated in figure 8 .

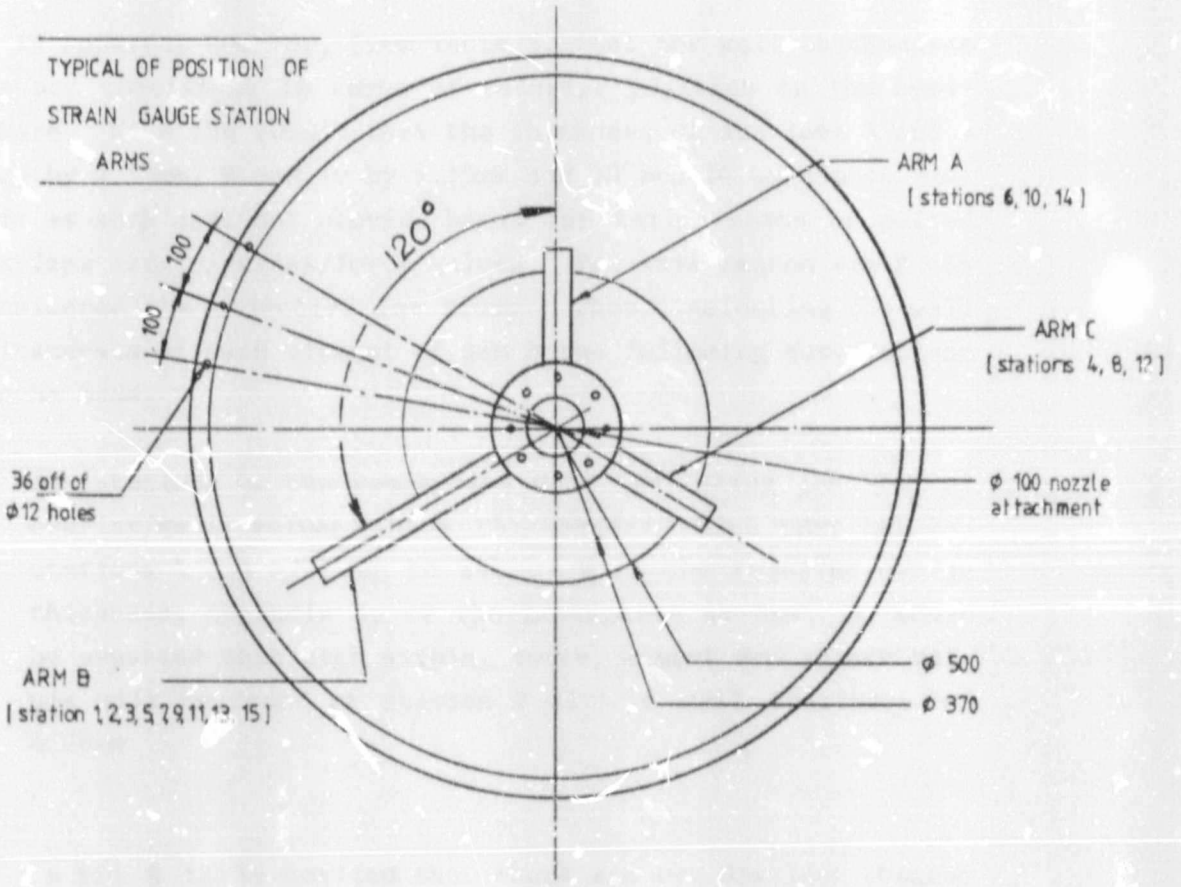


Figure 8 . Layout of the strain gauge arms.

The following indicates the arm in which each station is placed.

ARM A	:				6		10		14		
ARM B	:	1	2	3	5	7	9	11	13	15	
ARM C	:			4		8		12			

Arms A and C were designed to act as checks of the results of arm B.

It is apparent however, from Table 3, that the wall thicknesses are not consistent in terms of relative position on the hemisphere. With the result that the thickness of stations 3 and 4 vary by 2.53mm, 9 and 10 by 1.15mm and 13 and 14 by almost 2mm. This as such does not provide basis for taking means of paired stations strain/stress/force values. For this reason arm B was considered the objective for study. When considering the wall thicknesses of each element of arm B the following observations can be made.

- The stations on the hemisphere wall (excluding junction of overlay/wall values) have thicknesses which vary between stations 1 and 2 by up to 24% . With the required design thickness, Appendix A, of the hemisphere as 6mm, it would be expected that high strain, force, moment and stress values will be found at station 2 with a wall thickness of 6.86mm.

- In fig 9 it is noticed that there are two distinct changes in the radius of curvature of the wall/overlay junction between gauges 3 and 7. This would be a possible stress concentration area on the wall as it is an area of differing rates of change of wall thickness which possibly do not allow a linear distibution of stress.

- In analysing the glass content of each laminate element it may be noted that in the overlay region, woven roving exists on the outside surface. This is not according to the design specifications of Appendix A. This however, would not alter the stress values found as the strains are dependent on the glass content of the laminate.

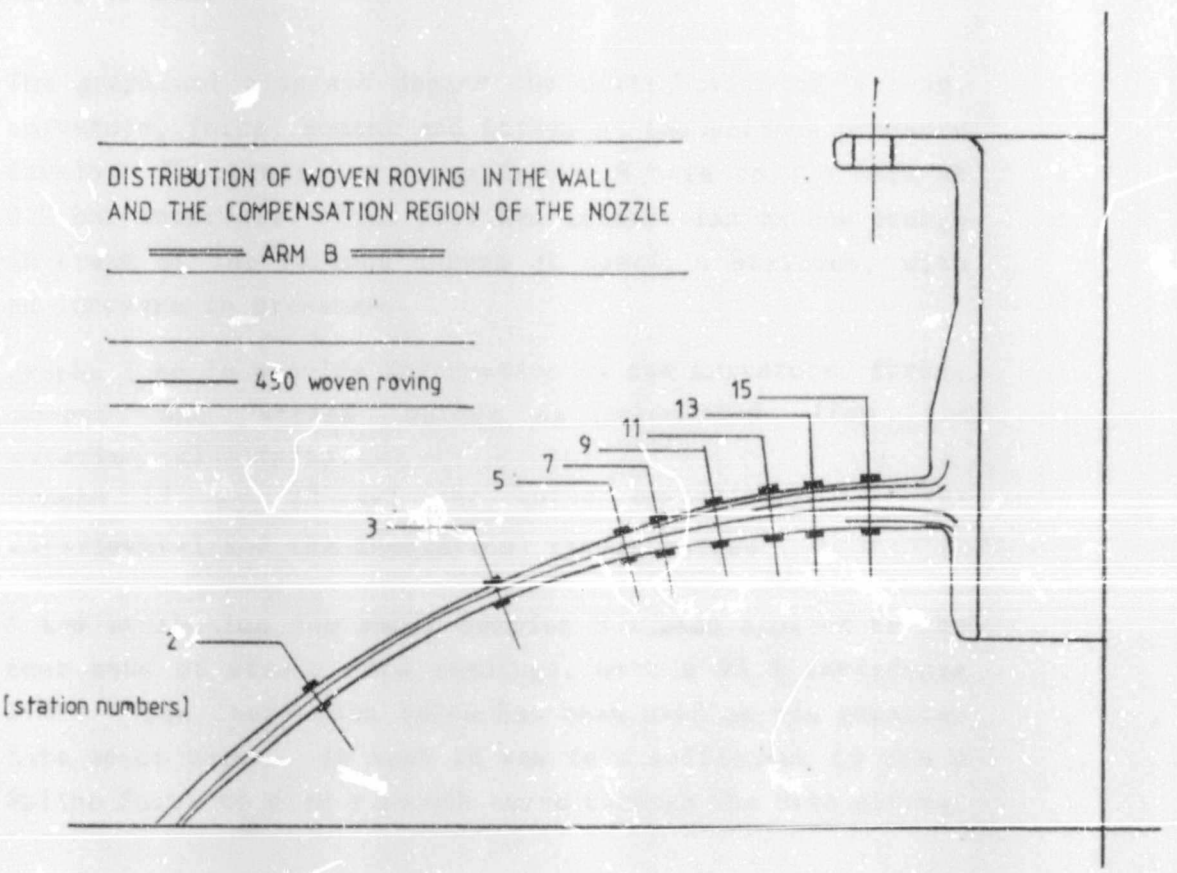


Figure 9 Distribution of the woven roving in the compensation region.

- The angles of lay-up of the woven roving of the laminate of station 13 (ARM B) are 45 °, +5 ° and -5 °. This is due to overlapping of the layers at this point on the hemisphere which occurs during manufacture. This is considered in the data processing of the mechanical characteristics of the laminate element when under load.

The geometr[illegible] the physical makeup of each laminate has thus been considered relevant when analysing the graphical outputs

of the test results of the nozzle ~~con~~figuration with respect to the lamination theory equations.

Graphical Outputs

- The graphical displays depict the distribution of strain, curvature, force, moment and stress at the various pressure levels. The pressures range from 0.8 bars to 1.6 bars at 0.2 bar intervals. This provides information on the change in trend of the various curves at specific stations, with an increase in pressure.

- Graphs 1 to 16 provide information on the curvature, force, moment and stress values as calculated from the experimental strains.
  Graphs 17 to 20 are the curve comparisons of the experimental and the theoretical stress values.

- A t-distribution for small samples has been applied to the four sets of strain data readings, with a 95 % confidence limit. The lower mean value has been used as the expected data point value. As such it was felt sufficient to use a Spline Curve to draw a smooth curve through the data points.

- The fact that the characteristic trends of the mechanical forces and stresses around the nozzle remained unknown called for the use of an unclamped spline curve. This method while being suitable for data points which are closely seperated, as in the nozzle region, may cause unexpected peaks where the points are far spaced, region between stations 1 and 3.

- The sign convention for curvature is positive when the slope of the strain distribution through the thickness of the laminate is negative.

- Curve comparisons only consider the 1.6 bar pressure level.

- The position of station 1 has been chosen as an arbitrary point on the hemisphere wall. This has permitted the data point to be positioned 50mm along the x axis of the graphs.

Table 3. Contents of each laminate element.

RESIN: DERAKANE 470-36

REINFORCEMENT: CSM - 450g/m² of chopped strand mat
WR - 450g/m² of woven roving
'C' glass tissue on both sides of each laminate

Laminate construction - outside to inside of vessel wall

Station No.	Thickness of reinforcement mm									Angle	Total Thicknes
	CSM	WR	CSM	WR	CSM	WR	CSM	WR	CSM	deg	(mm)
1	4,46	0,43	3,61	-	-	-	-	-	-	0	8,5
2	2,75	0,43	3,68	-	-	-	-	-	-	0	6,86
3	2,55	0,43	4,10	-	-	-	-	-	-	0	7,08
4	3,42	0,43	1,70	-	-	-	-	-	-	0	5,55
5	3,8	0,43	3,74	-	-	-	-	-	-	0	7,97
6	4,79	0,43	2,14	-	-	-	-	-	-	0	7,36
7	-	0,43	5,46	0,43	-	0,43	4,37	-	-	0	11,13
8	0,93	0,43	4,62	0,87	2,32	-	-	-	-	0	9,17
9	-	0,43	6,67	0,46	-	0,47	6,1	-	-	0	14,13
10	-	0,43	3,39	0,43	3,92	0,43	4,38	-	-	0	12,98
11	-	0,43	3,33	0,43	4,96	0,46	-	0,47	7,26	0	17,34
12	0,65	0,43	2,76	0,43	3,23	0,43	5,11	-	-	±45	13,04
13	0,65	0,43	4,19	0,43	3,58	0,46	-	0,47	7,12	45,±5	17,33
14	-	0,43	3,94	0,43	3,50	0,43	6,65	-	-	0	15,38
15	-	0,43	4,55	0,43	3,85	0,43	5,71	0,43	3,97	0	19,8

The angle of lay of the woven roving is decribed as follows with respect to the meridional and the hoop directions.

: Station (1 - 11) and (14 - 15) - Fibres in the principle directions.

: Station 12 - The two innermost WR layers are at +45° and -45° respectively to the principle directions.

: Station 13 - The second WR layer is at +45° and the two innermost layers are at +5° and -5° respectively to the principle directions.

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Name of thesis Stress Concentrations Around An Axisymmetrically Attached Nozzle On A Glass Reinforced Plastic Hemispherical Dome. 1987

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