EFFECT OF PREFORM SHAPE ON BUCKLING OF QUASI-ISOTROPIC THERMOPLASTIC COMPOSITE LAMINATES DURING SHEET FORMING

G.B. Mc Guinness, T.A. Nestor and C.M. Ó Brádaigh
Department of Mechanical Engineering
University College, Galway.

(A paper presented at the Third International Conference on Flow Processes in Composite Materials, University College, Galway, July 1994)

Abstract

Sheet forming of continuous fibre reinforced thermoplastic composite sheets is a potentially viable manufacturing process for high performance structural components. The development of a science base for understanding and predicting the behaviour of these materials under processing conditions is an active area of research. One important issue under consideration is the tendency of highly anisotropic composite melts to buckle out of plane when depressions are formed in them. This paper outlines a method which has been used to predict the stress patterns which are responsible for buckling, and presents experimental results which agree qualitatively with the predictions. A finite element formulation for Ideal Fibre Reinforced Newtonian Fluids, featuring the twin kinematic constraints of material incompressibility and fibre inextensibility, is used [1]. A mixed penalty finite element approach is adopted, with independent interpolation of tension and velocity solution fields. This formulation is implemented in the FEFORM finite element code. An analysis model consistent with an assumption of plane stress is used. Each ply is analysed individually, and average stress predictions for the laminate are obtained on this basis. Experiments have been conducted to investigate the relevance of the numerical analysis described here to real forming problems. Buckling patterns observed when quasi-isotropic sheets $(0/+45/-45/90)_s$ of different shapes are formed into a shallow hemispherical mould are shown. It is demonstrated that the numerical analysis correctly predicts the effect of altering the preform shape on the size or occurence of buckles at different sites on the sheet. This conclusion is of great assistance in developing our understanding of the physical nature of the buckling phenomenon, and determining the steps that may be taken to eliminate it in practical manufacturing situations.

1 Introduction

The development of efficient and cost effective composite forming methods will be necessary if fibre reinforced composites are to become widely used structural materials. Much recent research into sheet forming of composites has focused on the development of numerical simulation models. The ultimate goal of such research is to predict completely the behaviour of the composite laminate under processing conditions. We may also learn how to manipulate that behaviour to improve the quality of the final part by avoiding, for example, the conditions which may lead to buckling of the laminate. Finite element simulations have proven to be useful for these purposes in the sheet metal forming industry, and progress in numerical simulation of composites sheet forming has been encouraging. The purpose of this paper is to demonstrate the application of a previously developed mixed penalty finite element formulation to the analysis of forming of quasi-isotropic laminates into a hemispherical mould. A set of forming experiments is performed to exhibit the sensitivity of composite laminates to an out of plane buckling phenomenon at 45 degrees to the fibre directions, which has been labelled the shear buckling phenomenon. For quasi-isotropic materials, the buckles occur at the rim of the mould, at 0/+45/-45/90 degrees to the X axis. At these sites, the stress in the direction tangential to the rim of the mould which causes buckling acts on material with fibre directions at 0/+45/-45/90 degrees. Since these sites will all have the same stability conditions, we may directly compare the stresses acting at these sites and draw conclusions concerning buckles.

2 Diaphragm Forming Experiments

2.1 Previous Experiments

The purpose of the experimental program is to investigate the effect of preform shape on the ocurrence of out of plane buckling in sheet forming shapes of double curvature. Previous experimental work in this area has concentrated on forming into hemispherical moulds of different depths and radii, either using a pressurised autoclave[2] or a punch[3]. Initially, all experiments involved circular preforms. Results have been published for unidirectional, cross ply and quasi-isotropic cases and it was observed that buckles form at 45 degrees to the fibre directions in each case[2]. It was also observed that faster forming rates increased the severity of buckling[3]. For unidirectional and cross ply circular laminates, the observation was recorded that the severity of buckling increased for larger sheet diameters[2]. Previous numerical studies using the FEFORM code have shown agreement with this trend[4].

2.2 Equipment

The diaphragm forming experiments described in this paper were performed in a computer controlled thermoforming autoclave[5]. This autoclave operates at pressures of up to 2.06 MPa, and at temperatures of up to 400 degrees centigrade. A LVDT displacement transducer offers the possibility of monitoring the deflection of the composite lay-up during forming, or of controlling the deflection rate through the use of control software. Heating and cooling of the autoclave may also be controlled by a personal computer. Full details of the experimental equipment used may be found in [5].

The emphasis in this paper will be on the behaviour of quasi-isotropic laminates of different sizes and shapes. The motivation for the experiments described in this paper is an investigation of the shear buckling phenomenon. The mould used is a shallow hemispherical mould, known as the Female-A mould, which has a depth of 19 mm. This shallow mould is chosen to minimise the effect of elastic bending stresses due to fibres deforming into the mould. The diameter of the cavity is 3 inches, while the overall diameter of the mould is 8.5 inches.

The composite material involved in the present study is APC-2 carbon fibre reinforced PEEK, produced by I.C.I.. The diaphragms used are Upilex R polymeric diaphragm sheets produced by UBE.

2.3 Procedure

Fast forming rates were required to cause buckles in quasi-isotropic laminates for the shallow mould. These were acheived by pressurising both the autoclave and the cavity of the mould to 60 psi at 380 degrees centigrade. The laminate was then allowed to consolidate before forming (Figure 1(a)). The pressure in the cavity of the mould is then released, allowing the full 60 psi autoclave pressure to form the laminate into the mould (Figure 1(b)). The displacement of the centre of the top diaphragm in the lay-up is recorded using the LVDT. An example of the displacement versus time relationship for a typical experiment carried out in this manner is given in Figure 2. We can see that the laminates form at a rate in the region of 10 mm/sec

2.4 Results

Forming experiments were carried out using rectangular preforms of 6 inches length and 4, 5 and 6 inches width respectively (Figure 3). The formed shapes from these experiments are shown in Figure 4. All laminates exhibit obvious buckling. The prominent buckles for the 4 inch x 6 inch rectangle appear at the two points on the rim of the mould which are closest to the edge of the laminate. No other buckles are cleary discernible. The buckles are clearly caused by a stress which acts along the direction parallel to the 6 inch side of the rectangle. At the buckling site, this stress acts tangentially to the rim of the mould, and it acts on an element of material which has 4 different directions of reinforcement. At that point, these directions of reinforcement are at 0, +45, -45 and 90 degrees to the direction of the action of the stress responsible for buckling.

Considering the 5 inch x 6 inch rectangle, buckles are clearly evident again in the same position, but a second, less severe, set of buckles has formed at 90 degrees to the first set. The buckles form symmetrically for the 6 inch square experiment, large ones at the original buckling sites, and new smaller ones at approximately 45 degrees to these.

A further experiment was carried out to assess the effect of cutting across two corners from a square preform. The result of this test is depicted in Figure 5. It seems clear from these experiments that buckles may be expected to form most severely at the positions on the sheet which have the least amount of surrounding flange material.

3 Modelling of Sheet Forming

3.1 Continuum Model for Composites Sheet Forming

The continuum model used to represent the behaviour of the composite melt during forming is that of the Ideal Fibre Reinforced Newtonian Fluid. The constitutive relationship for this type of model involves the two kinematic constraints of material incompressibility and fibre inextensibility. The constitutive relationship is given by Rogers [6] as :

$$\sigma_{ij} = -P\delta_{ij} + Ta_i a_j + 2\eta_T D_{ij} + 2(\eta_L - \eta_T)(a_i a_k D_{kj} + a_j a_k D_{ki})$$

where σ_{ij} is the Cauchy stress tensor and η_L and η_T are the longitudinal and transverse shear viscosities respectively. P is the arbitrary hydrostatic pressure associated with the constraint of incompressibility, and T denotes the arbitrary tension associated with the constraint of fibre inextensibility. d is the rate of deformation tensor. This may be reduced to the following set of equations when conditions of plane stress apply.

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{bmatrix} = \begin{bmatrix} D_{11}+C_{33} & D_{33} & D_{16} \\ D_{33} & D_{22}+D_{33} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} d_{11} \\ d_{22} \\ 2d_{12} \end{bmatrix} + \begin{bmatrix} Tm^2 \\ Tn^2 \\ mnT \end{bmatrix}$$

where $m = \cos\theta(t)$ and $n = \sin\theta(t)$, and the terms of the viscous constitutive matrix are given as follows :

$$D_{11} = 2\eta_T(1 - 2m^2) + 4\eta_L m^2$$
$$D_{22} = 2\eta_T(1 - 2n^2) + 4\eta_L n^2$$
$$D_{33} = 2\eta_T$$
$$D_{16} = C_{26} = 2(\eta_L - \eta_T)mn$$
$$D_{66} = \eta_L$$

It should be noticed that this system features only the arbitrary tension stress. The incompressibility constraint may be satisfied by adjusting the deformation rate in the through thickness direction.

The diaphragm material is represented as an isotropic viscous fluid, using the relationship

$$\sigma_{ij} = -P\delta_{ij} + 2\eta d_{ij}$$

which is characterised by the single viscosity η. For plane stress conditions, the following reduced set of equations apply :

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{bmatrix} = \begin{bmatrix} 4\eta & 2\eta & 0 \\ 2\eta & 4\eta & 0 \\ 0 & 0 & \eta \end{bmatrix} \begin{bmatrix} d_{11} \\ d_{22} \\ d_{12} \end{bmatrix}$$

3.2 Finite Element Formulation

A mixed penalty finite element formulation has been developed for the Ideal Fibre Reinforced Newtonian Fluid continuum model [1], involving independent discretisation of the velocity and tension solution fields. Details of the derivation of the formulation are given in [1], and will not be repeated here. The final formulation takes the form :

$$\left\{\mathbf{K}+\alpha\mathbf{K}^t\left(\mathbf{M}^t\right)^{-1}\left(\mathbf{K}^t\right)^T\right\}\mathbf{a}^v=\mathbf{f}$$

where the matrices are given by:

$$\mathbf{K}_{ij}=\int_\Omega\left(\mathbf{B}_i^v\right)^T\mathbf{D}\mathbf{B}_j^v\,d\Omega \qquad \mathbf{K}_{ij}^t=\int_\Omega\left(\mathbf{B}_i^v\right)^T\mathbf{a}\mathbf{N}_j^t\,d\Omega$$

$$\mathbf{f}=\int_\Gamma\left(\mathbf{N}_i^v\right)^T\mathbf{t}\,d\Gamma \qquad \mathbf{M}_{ij}^t=\int_\Omega\mathbf{N}_i^t\mathbf{N}_j^t\,d\Omega$$

where $\mathbf{N}^t$ and $\mathbf{N}^v$ denote the interpolation functions for the tension and velocity fields respectvely and α is the penalty number. The solution for nodal tensions $\mathbf{a}^t$ may be obtained from the solution for nodal velocities $\mathbf{a}^v$ as follows :

$$\mathbf{a}^t=\alpha\left(\mathbf{M}^t\right)^{-1}\left(\mathbf{K}^t\right)^T\mathbf{a}^v$$

4 Analysis Model and Results

4.1 Analysis Model

The development of the mixed penalty finite element formulation involves the assumption of plane stress conditions. The analysis models which are used to represent the experiments described in Section 2 are therefore planar. A schematic of a model used to analyse forming of a rectangular sheet into a circular cavity is depicted in Figure 6. We are considering the behaviour of the flange region of the lay-up, on the basis that this is where shear buckling happens, and that the different geometric features which have been tested experimentally may easily be incorporated in the model. The outer region, which is marked as representing diaphragm material, is constrained at the outer edges, to represent the clamping of diaphragm material in real forming situations. A uniform unit hydrostatic pressure is applied to the inner radius of the model, in an attempt to mimic the application of the hydrostatic pressure to form the part against the tool in the experiments.

The symmetry conditions for these problems must be considered in the context of the following assumption. For the purposes of analysing multidirectional materials, some consideration must be given to the manner in which the different plies interact with each other during forming. This matter is currently the subject of research[, and ultimately physical laws will be used to represent the real behaviour in numerical simulations. Experimental analysis has shown that a resin rich layer exists between two adjacent plies during forming, which facilitates sliding between plies. However, as a simple approximation to this behaviour, we will assume that individual plies deform independently of each other. This means that we analyse each ply independently, and calculate an average condition for the laminate. The consequences for the symmetry of the model are as follows. If we wish to analyse a quasi-isotropic rectangular laminate, this will include some +/- 45 degree plies. Even though the laminate as a whole will exhibit symmetry about the X and Y axes, the solution fields for these particular individual plies will not. Therefore simply analysing a quadrant of the problem will not yield a correct solution, and the full model should be used.

The shear viscosities used in the analysis are η_L = 6000 Pa.sec., η_T = 4000 Pa.sec. for the APC-2 and $\eta = 10^8$ Pa.sec. for the Upilex R polymeric diaphragms.

4.2 Stability Considerations

A complete analysis of the buckling phenomena discussed in this paper would require a stability analysis of the composite laminate as it deforms into the mould. The different components of stress predicted for the laminate would then have to be considered in the light of the manner in which the material might be expected to respond. In the case of quasi-isotropic laminates, experiments reported here and elsewhere [2] suggest that buckling will always initiate in a direction at 0/+45/-45/90 degrees to the fibre directions, and, for a female hemispherical mould, will always begin at the rim. Without attempting a proper stability analysis at this stage, we will use these observations to consider the implications of our analysis results. We examine the tangential stress predicted along the inner radius of our model, because this stress acts in the direction of buckling at the likely buckling sites. We note that, though the solution values for tangential stress at all points along the inner radius are shown, these are not all of the same significance, because they act along material directions which have different susceptibilities to buckling. However, at each of the possible buckling sites, it is fair to say that the laminate will have the same resistance to buckling. Our comments on the numerical results are made on this basis.

4.3 Mesh Sensitivity

The issue of the sensitivity of axial stress predictions to the density of the mesh and to distortion of the elements in the region of the tension stress singularity must be addressed. In the past, when FEFORM was used to model circular and square preform shapes, it was possible to use meshes of uniform density with regularly shaped elements. Modelling the rectangular shapes described, it is no longer easy to construct a mesh which is completely uniform. In order to assess the mesh density needed to reasonably represent the true stress conditions in problems of this kind, a convergence study was carried out using a simple mesh of a quadrant of a circle (Figure 7). The inner radius of the model is 12.7 mm, while the outer radius of the composite material region is 50.8 mm. The outer radius of the diaphragm region is 107.95 mm. This mesh is typical of those used in the analyses described in [3], and the same symmetry and boundary conditions apply. A unit normal pressure is applied to the inner radius. Three different meshes were used to solve this problem. The first, coarsest, mesh has 143 nodes and 30 elements as shown in Figure 7. The axial stress predictions for this mesh are shown in Figure 8. The ratio of the axial stress singularity to the applied pressure is predicted as -246. Figure 9 shows the solution for a much denser mesh (2009 nodes, 540 elements), and it is qualitatively similar to that of the coarse mesh. The value of the tension stress singularity is now -319. Inspection of the two results suggests that the coarse mesh works surprisingly well, and is only significantly inaccurate at the point of the singularity. The results of a study of the convergence of the stress at the singular node are presented in Figure 10.

The second factor we wish to investigate is the accuracy of predictions in the region of elements with poor aspect ratios. The same problem is considered, but this time elongated elements are used. A sample mesh, consisting of 539 nodes and 120 elements, is shown in Figure 11, with the axial stress predictions depicted in Figure 12. The value of the tension stress singularity ratio is significantly underpredicted, at only -113.

4.4 Mesh Design

The studies described above were intended to guide the mesh design for the analysis of the forming of rectangular laminates. In the light of these results, it is clear that element distortions have a potentially more serious effect on the calculation of tension stress singularities than mesh density does. Each of the meshes used to model the forming of rectangular quasi-isotropic laminate (for example, the 5 inch X 6 inch model, shown in Figure 13) has a varying mesh density around the inner radius. This was done in order to reduce element distortion in this area. Similar meshes representing laminates of 4 inch, 4.5 inch, 5.5 inch and 6 inch widths have also been constructed, and are used in the analysis that follows. In order to further minimise the possibility of mesh irregularities spoiling the relationship between different analysis results (and misleading us about the relationship between stress predictions for different laminate shapes), the central square region of the mesh is identical for each case. Only the outer region of each mesh varies.

4.5 Results

The results of the finite element parameter study to investigate the effect of varying sheet width are now discussed. We initially consider the results for the one ply unidirectional case. In order to illustrate the contributions of the various different plies to the averaged stress state that we calculate for the laminate, we will consider the case of the 4.5 inch rectangle. The tangential stress distributions at the inner radius of the model for the case of each of the four fibre directions are shown in Figure 14. A contour plot of the tangential stresses for the +45 degree fibre direction case is given in Figure 15. The mesh used to analyse the 5.5 inch case is shown in Figure 16, and the average tangential stress distribution for the laminate is displayed in Figure 17. The tangential stress pattern is clearly influenced by the bands of compressive axial stress which occur where fibre directions run tangent to the inner radius of the model. These bands are similar in nature to those discussed in the mesh sensitivity study. Figure 18 looks closely at the region of the model close to the inner radius, and we can see that the stress singularities at the 0 degree and 90 degree points are much more severe than that at the 45 degree point.

To determine more accurately the relative sizes of the different stress concentrations, and to compare between the different sheet sizes, we look at Figure 19, which gives the tangential stress distributions at the inner radii of the models, in the 0 to 90 degree quadrant. Firstly, let us consider the result for a 6 inch square, which corresponds with an experiment reported in Section 2. The tangential stress at the 0 and 90 degree points are the same, as would be expected, given the symmetry of the shape. These stresses are considerably in excess of those reported at the 45 degree point. This offers an explanation for the severe buckles which form at 0 and 90 degrees in the experiments, and the slight buckles which appear at the 45 degree point. Looking at the predictions for the rectangular sheets, a clear trend emerges. As the width of the laminates is reduced, the tangential stress which causes buckling increases at both the 0 degree point and the 90 degree point, but in each case the 0 degree site bears the greater stress. This is also in agreement with the experiments reported in Section 2 where buckles form more severely at the 0 degree site. The relationship between sheet width and predicted tangential stresses responsible for buckling is approximately linear, as demonstrated in Figure 20.

Finally, we consider the case of the 6 inch square laminate with two opposite corners cut away, the experimental result for which was seen in Figure 5. The mesh used for this analysis is given in Figure 21, and the results will be given in tabular form, for ease of comparison with the predictions already reported for the 6 inch square. Tangential stress results at each buckling site for both of these cases are presented in Table 1, with the angle measured in degrees from the positive X axis.

Angle (Degrees)	0	45	90	135	180
6 Inch Square	-3.435	-0.547	-3.435	-0.574	-3.435
6 Inch Square with corners cut	-1.242	-0.508	-1.259	-0.696	-1.242

Table

The most obvious difference between the two cases is at the 0, 90 and 180 degree points. The value of the stress singularity at these points is considerably lower for the case of the laminate with the truncated corners. This coincides with the points around the inner radius of the model where the tangential fibres have been shortened. The stress concentrations reported where these fibres are tangent to the rim of the mould in the 0 and 90 degree plies are substantially reduced. There is only a small effect on the stresses predicted for the + 45 and -45 degree plies, which may be related to the fact that the singular fibres in these cases have not been shortened at all. It must be noted that this result would suggest that, for the new truncated case, one would expect buckles to form at the 135 degree point with the same severity as the 45 degree point. This is not in agreement with the experimental results. The reason for this may that the amount of surrounding material at the 135 point inhibits buckling to a greater degree than at the 45 degree position. Effects of this kind have not yet been included in the model.

Conclusions

Preform shape has an important effect on the formation of buckles in composites sheet forming. For rectangular quasi-isotropic laminates, narrow rectangles exhibit different buckling behaviour to squares, with buckles forming more severely on the sites with least surrounding flange material. The finite element model stress results can be used to explain and predict the distribution of buckles. The major contributing factor to the stresses responsible for the most severe buckles are tension stresses along fibres which run tangent to the rim of the mould. These stresses are significantly less for the + 45 and -45 degree square plies, leading to a reduced tendency to buckle at the 45 degree site. The need for a proper stability analysis is highlighted by the comparison between the numerical and experimental results for the truncated square laminate.

Acknowledgements

The authors would like to acknowledge the financial support of BRITE EURAM contract BE 5092-92. The authors would also like to thank final year student Dara Ely and the staff of the Departments of Mechanical and Electronic Engineering at University College, Galway for their help in the work reported in this paper.

References

[1] Ó Brádaigh, C.M. and Pipes, R.B.: *Finite Element Analysis of Composite Sheet Forming Processes*, Composites Manufacturing Vol 2 No. 3/4 1991, pp. 161-171

[2] Ó Brádaigh, C.M., Pipes, R.B and Mallon, P.J.: *Issues in Diaphragm Forming of Advanced Composites*, Polymer Composites, Vol. 12, No. 4, August 1991, pp. 246-256

[3] Ó Brádaigh, C.M. and Pipes, R.B.: *A Punch Deformation Experiment for Sheet Forming of Thermoplastic Composites*, Nethererland Congress Centre, The Hague, October 1991.

[4] Ó Brádaigh, C.M., Mc Guinness, G.B. and Pipes, R.B.: Numerical Analysis of Stresses and Deformations in Composite Materials Sheet Forming : Central Indentation of a Circular Sheet, Composites Manufacturing, Vol. 4, No. 2, 1993.

[5] Monaghan, M.R. and Mallon, P.J.: *Development of a Computer Controlled Autoclave for Forming Thermoplastic Composites*, Composites Manufacturing, Vol. 1, No. 1, pp8-14

[6] Rogers,T.G. Rheological Characterisation of Anisotropic Materials, Composites, 20(1):21-27, January 1989.

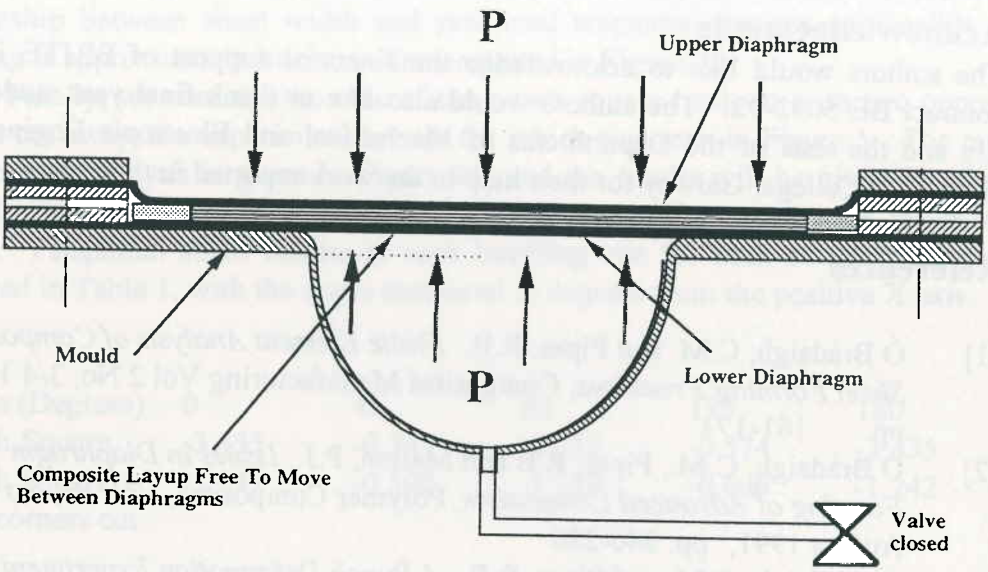

Figure 1(a) Laminate consolidating before forming.

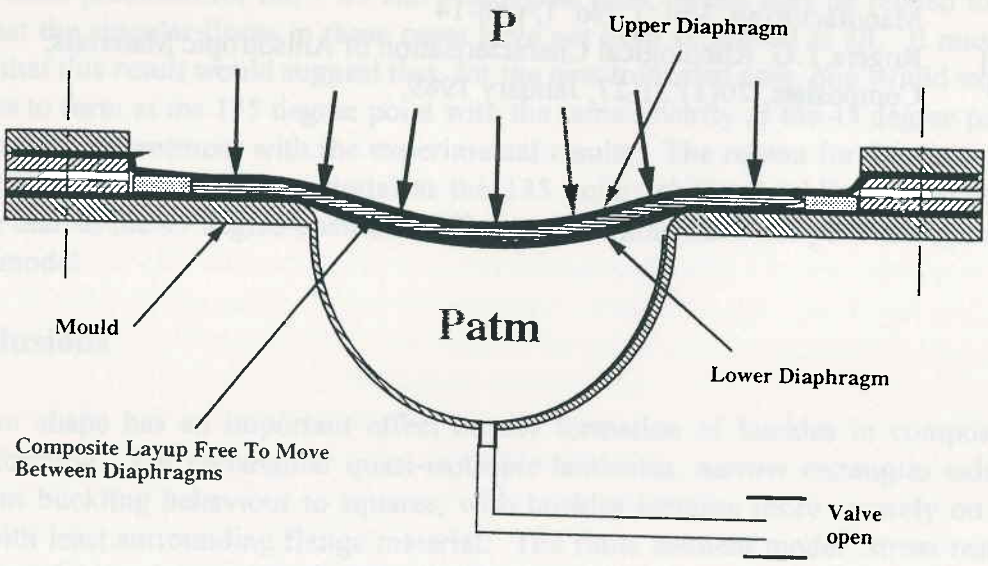

Figure 1(b) Laminate formed as cavity pressure released

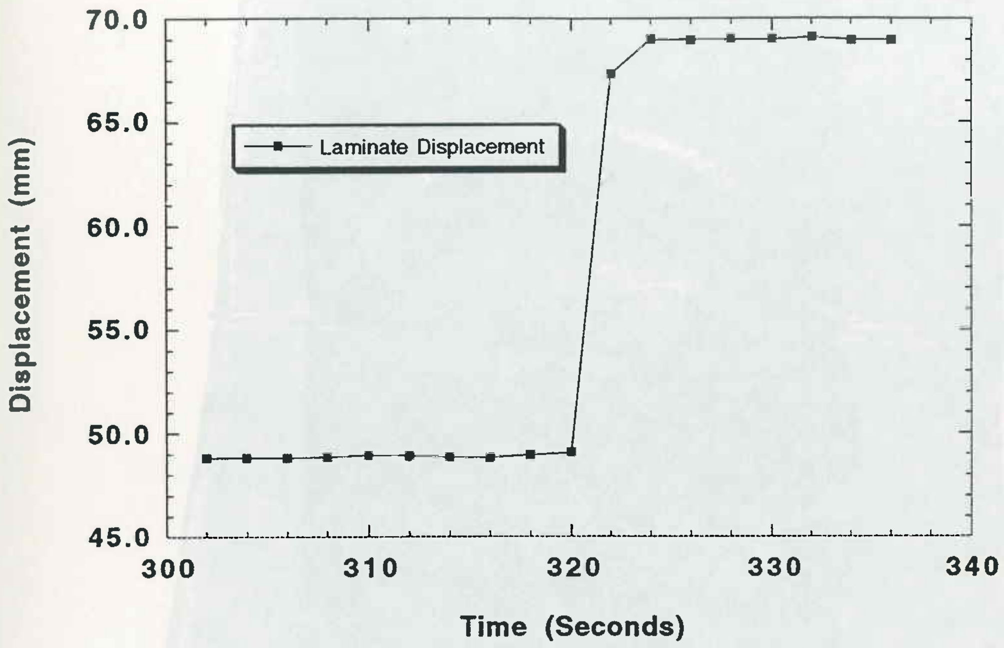

Figure 2 Displacement versus time for the deforming laminate.

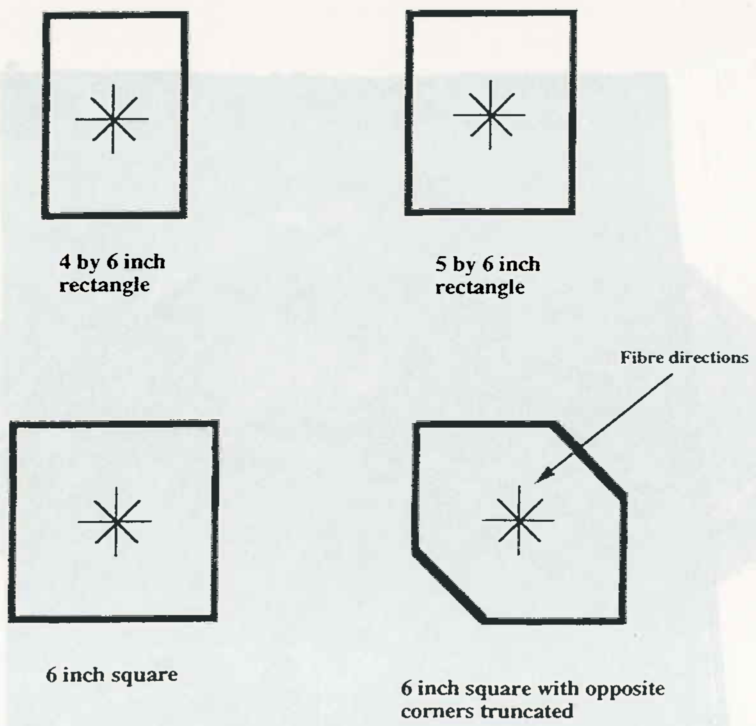

Figure 3 Quasi-isotropic preform shapes for forming experiments

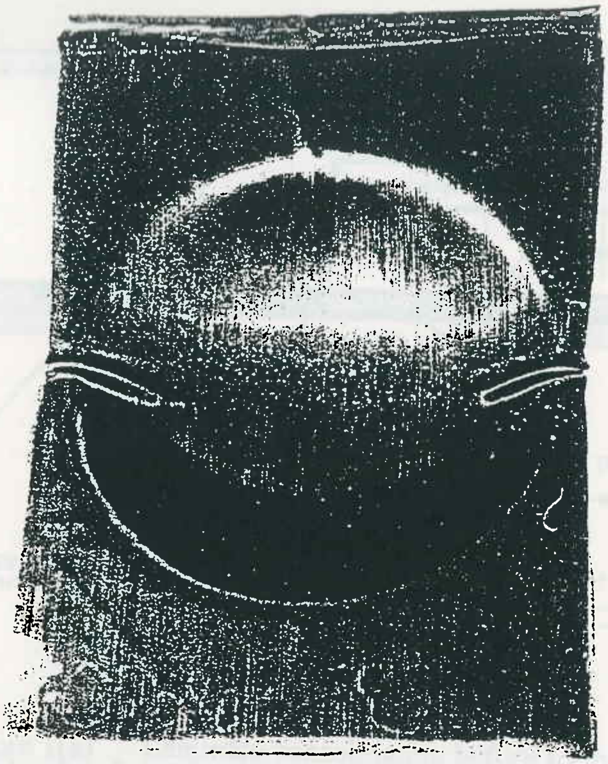

Figure 4(a) Formed 4 inch wide laminate

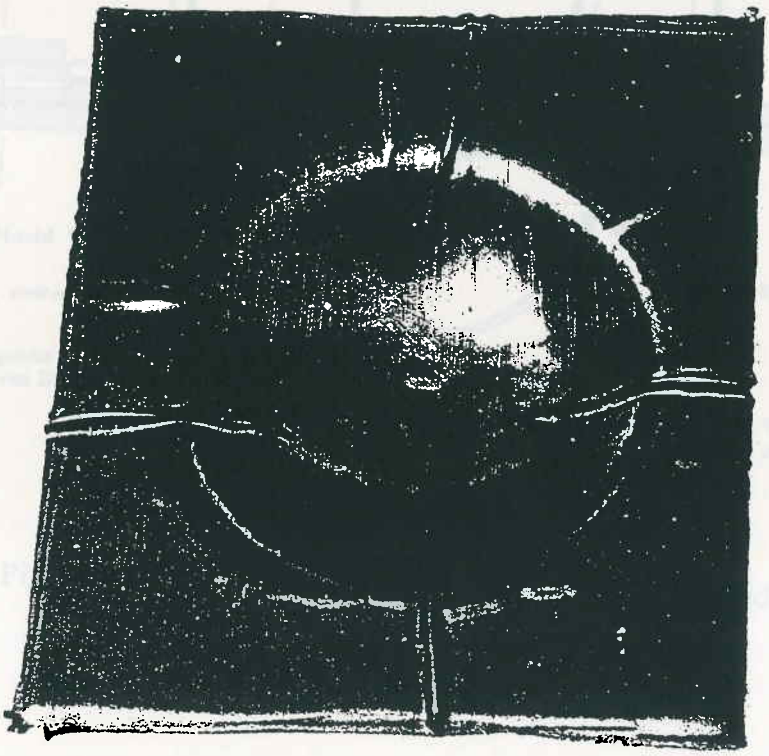

Figure 4(b) Formed 5 inch wide laminate

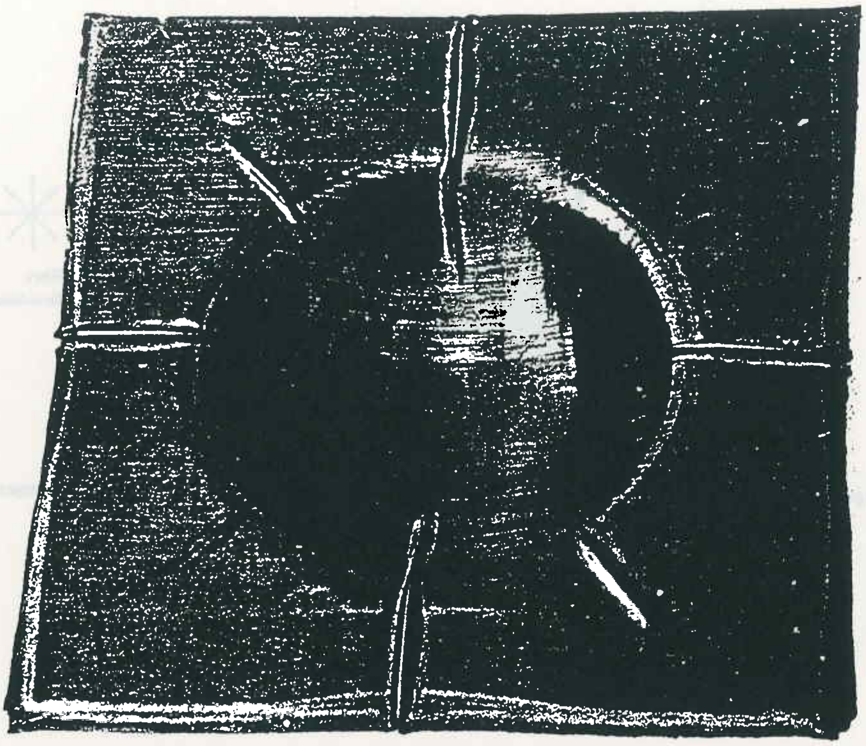

Figure 4(c) Formed 6 inch wide laminate

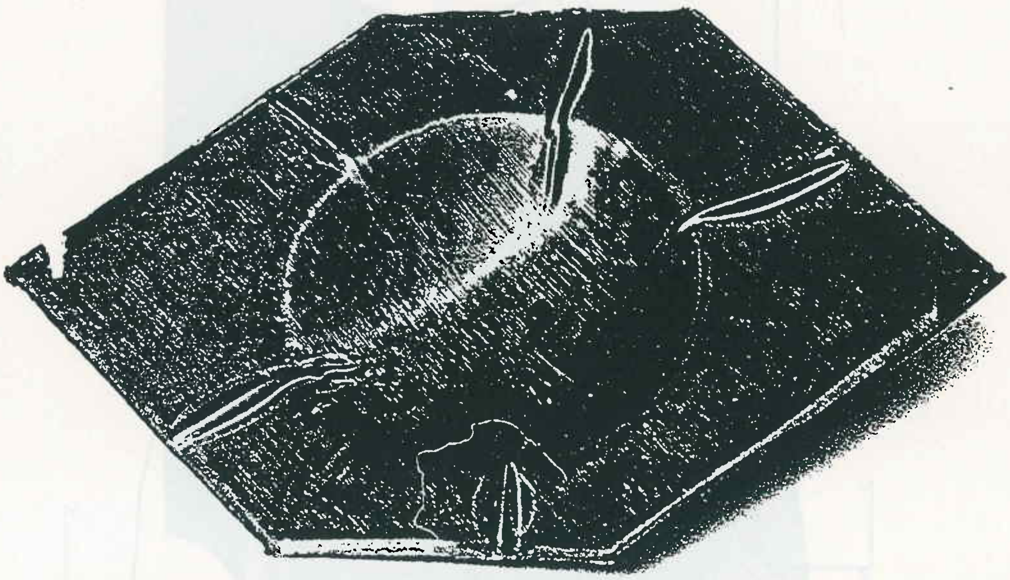

Figure 5 Formed laminate : 6 inch square with corners removed.

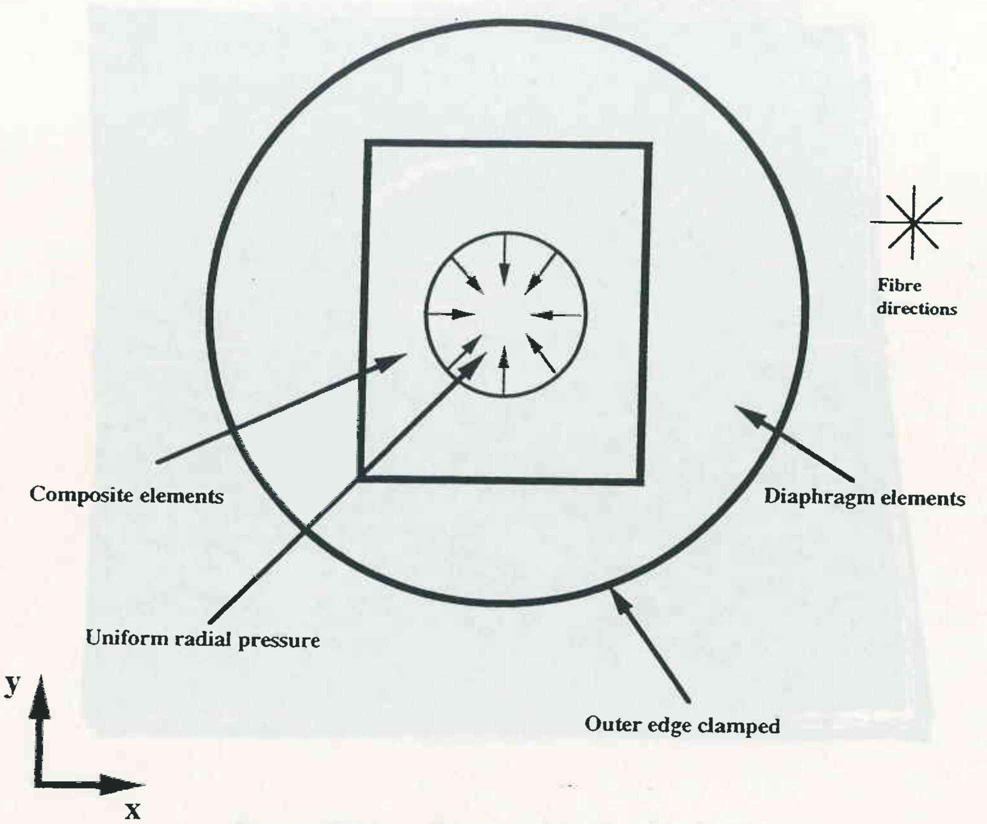

Figure 6 Schematic of planar forming model with boundary conditions

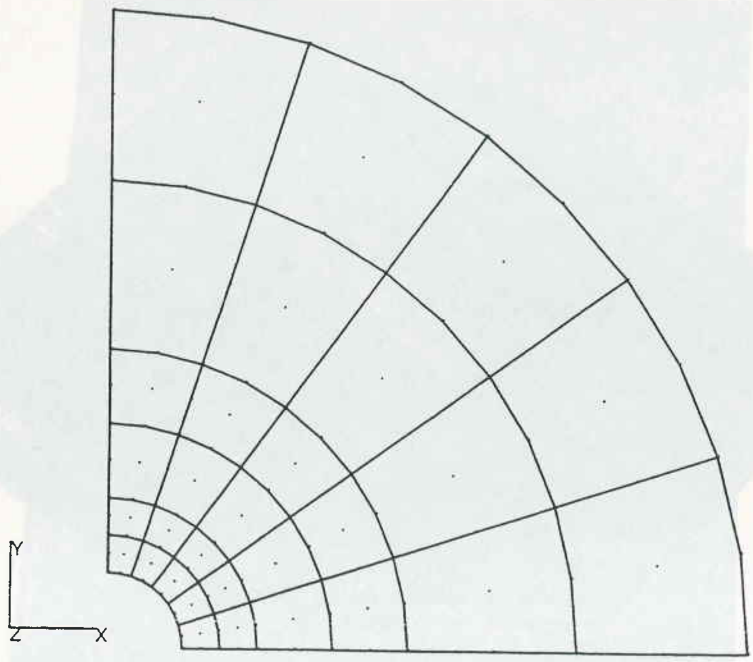

Figure 7 143 node, 30 element mesh for forming with a unidirectional circular sheet

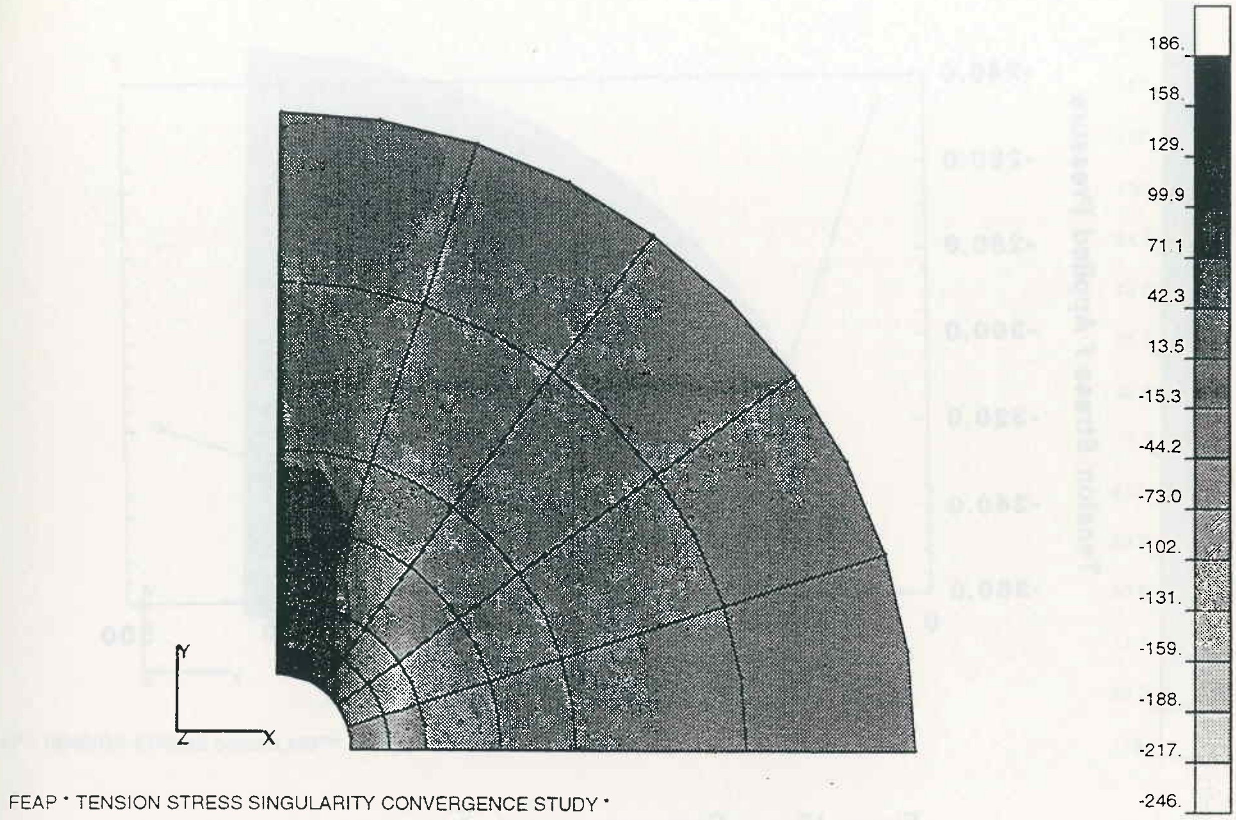

Figure 8 Axial stress predictions for 143 node, 30 element mesh.

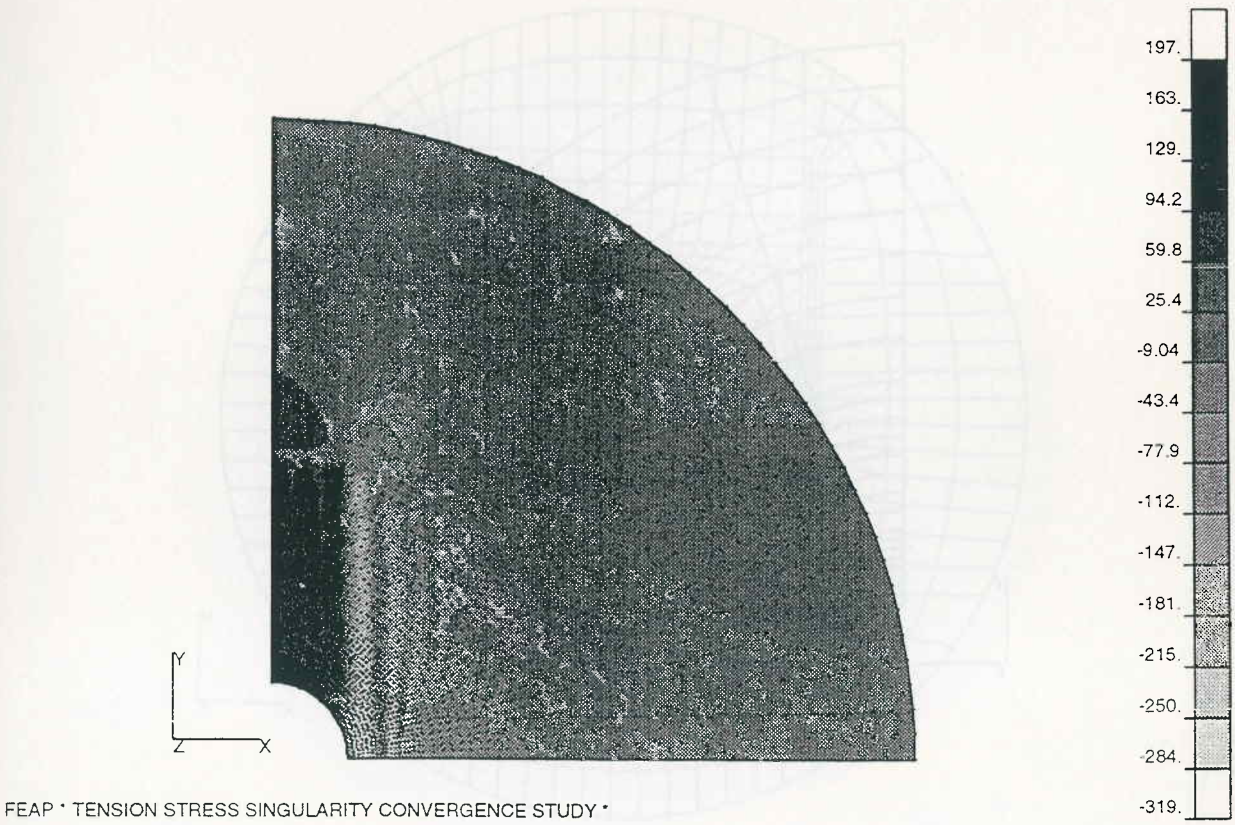

Figure 9 Axial stress predictions for 2009 node, 480 element mesh.

ular

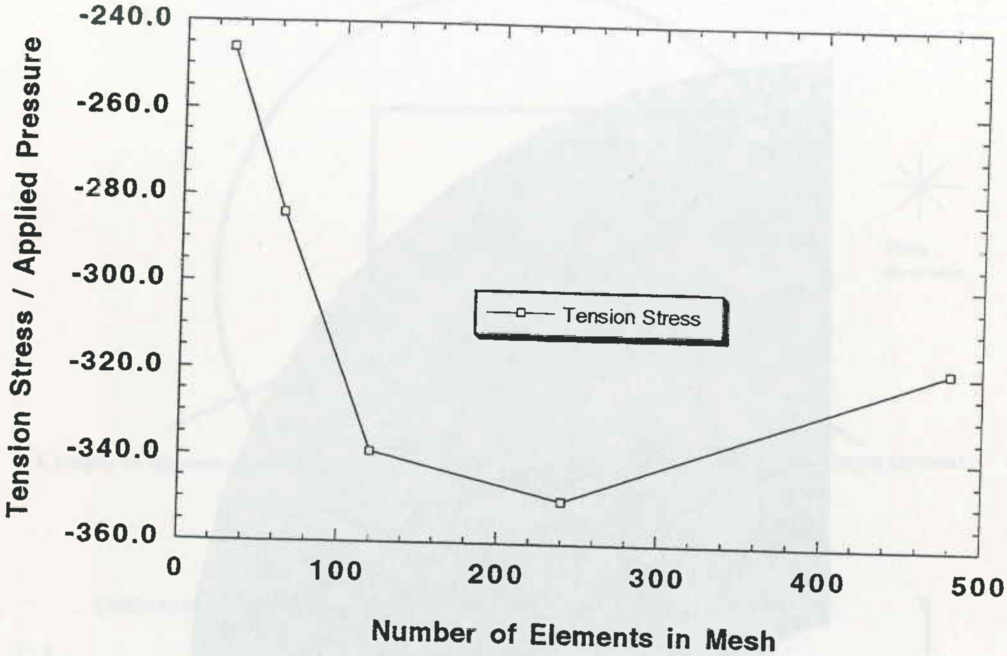

Figure 10 Convergence study for axial stress.

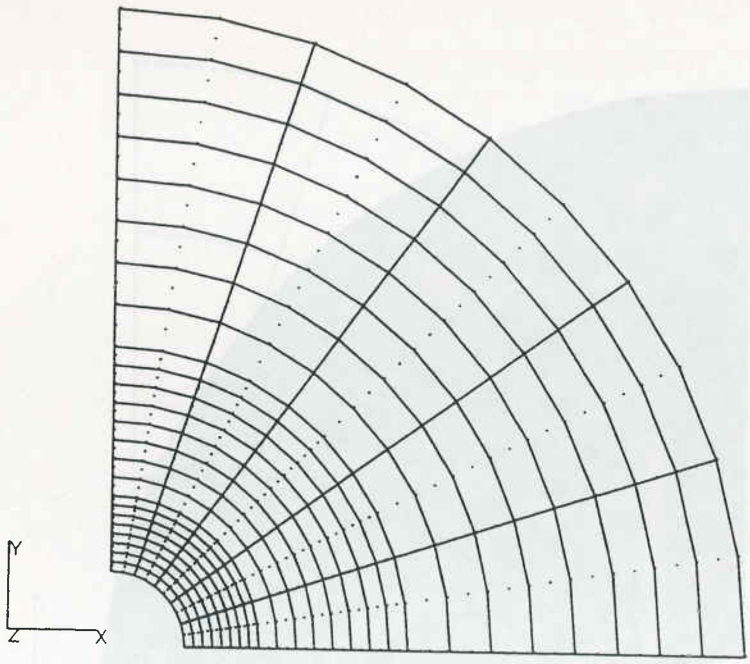

Figure 11 539 node, 120 element mesh for forming with unidirectional circular sheet.

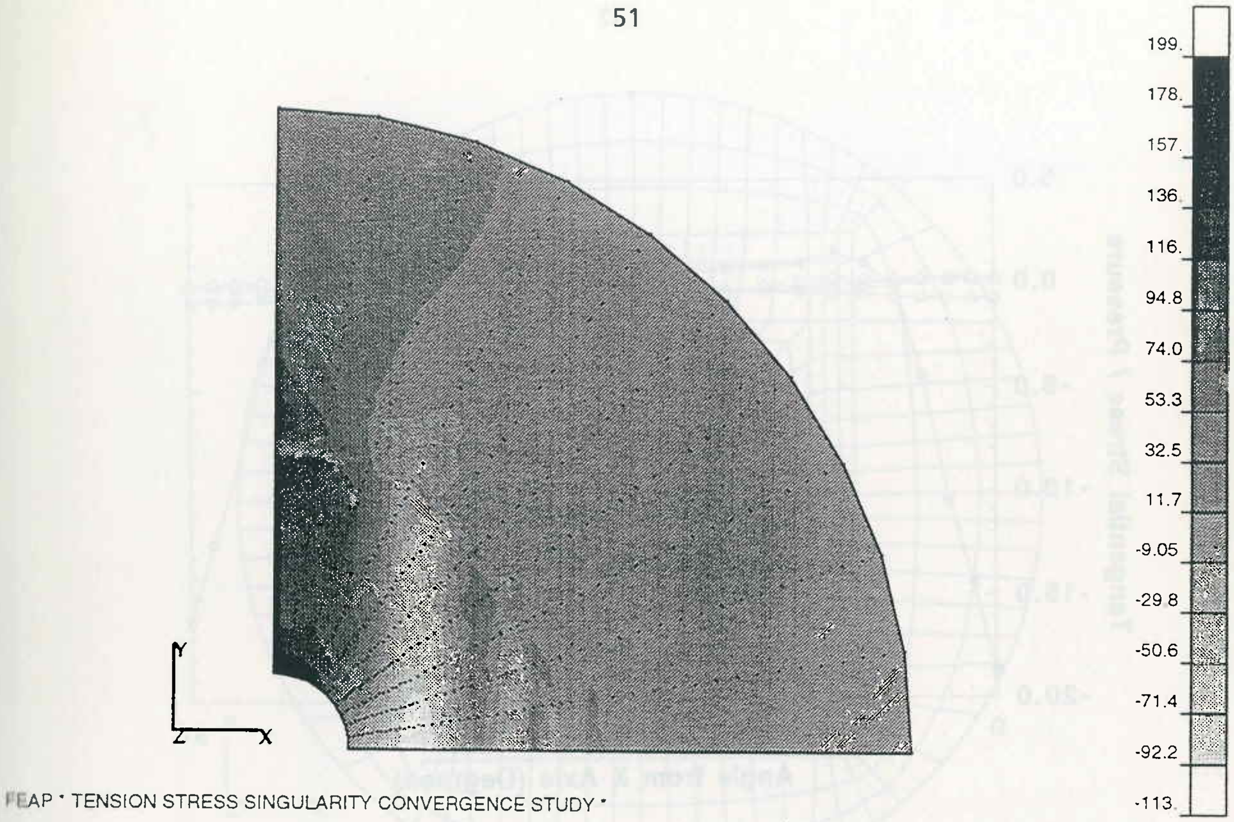

Figure 12 Axial stress predictions for a mesh with high aspect ratio elements.

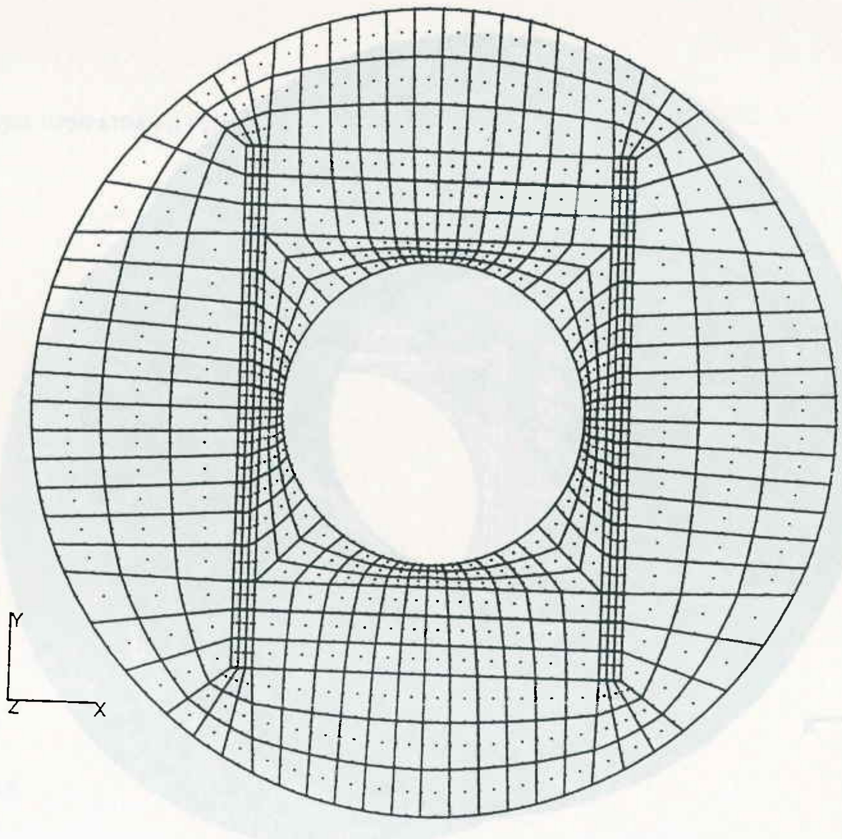

Figure 13 Mesh used to analyse 5 inch X 6 inch quasi-isotropic laminate.

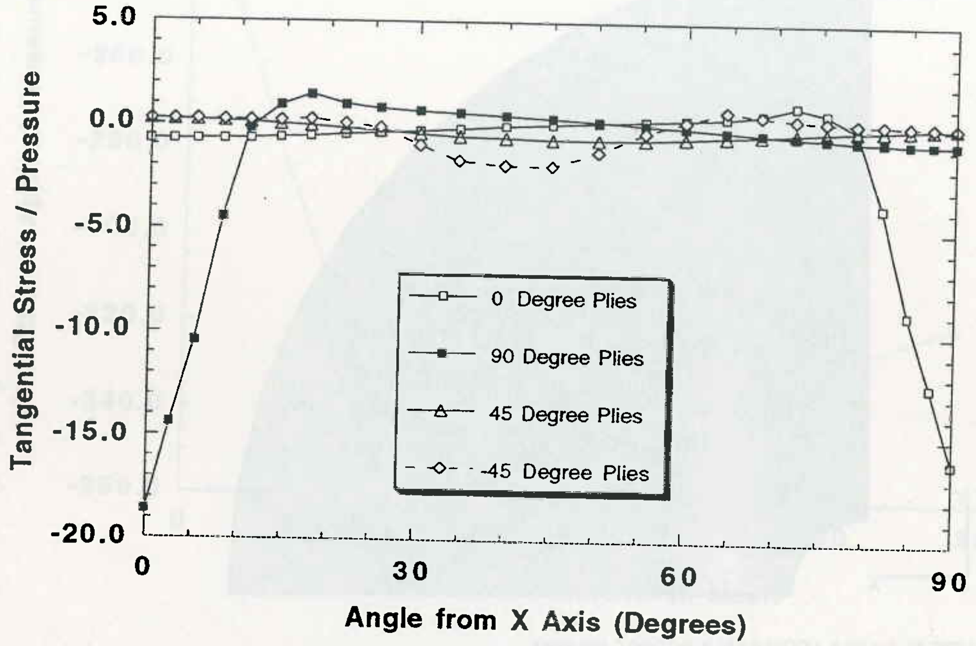

Figure 14 Tangential stress distributions for individual plies (5 inch X 6 inch)

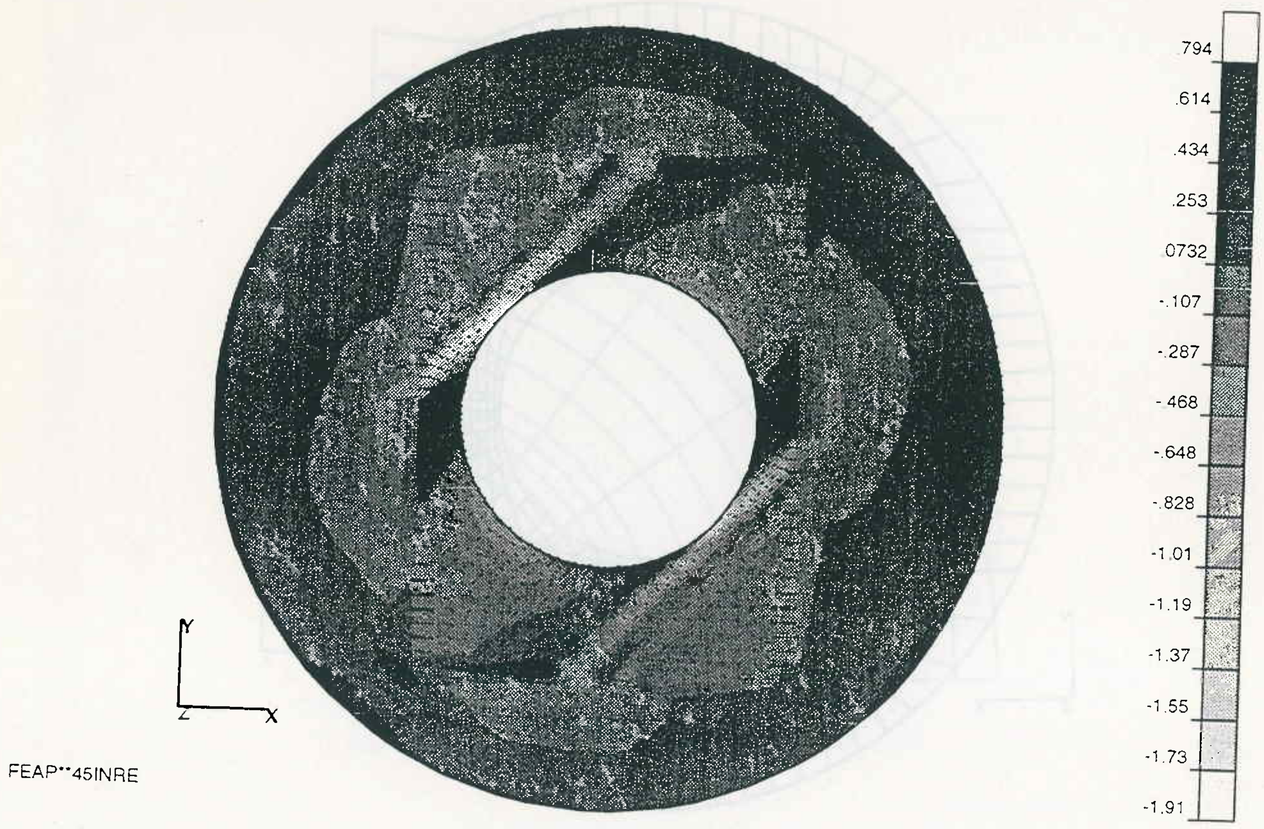

Figure 15 Contour plot for tangential stress inrectangular laminate.

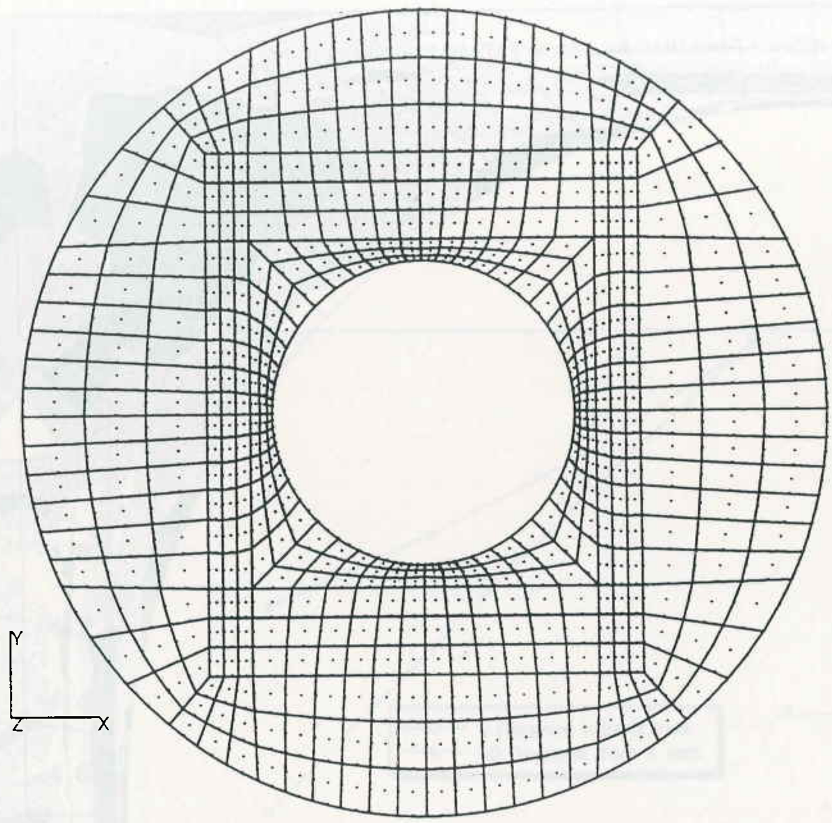

Figure 16 Mesh used to analyse 5.5 inch X 6 inch quasi-isotropic laminate.

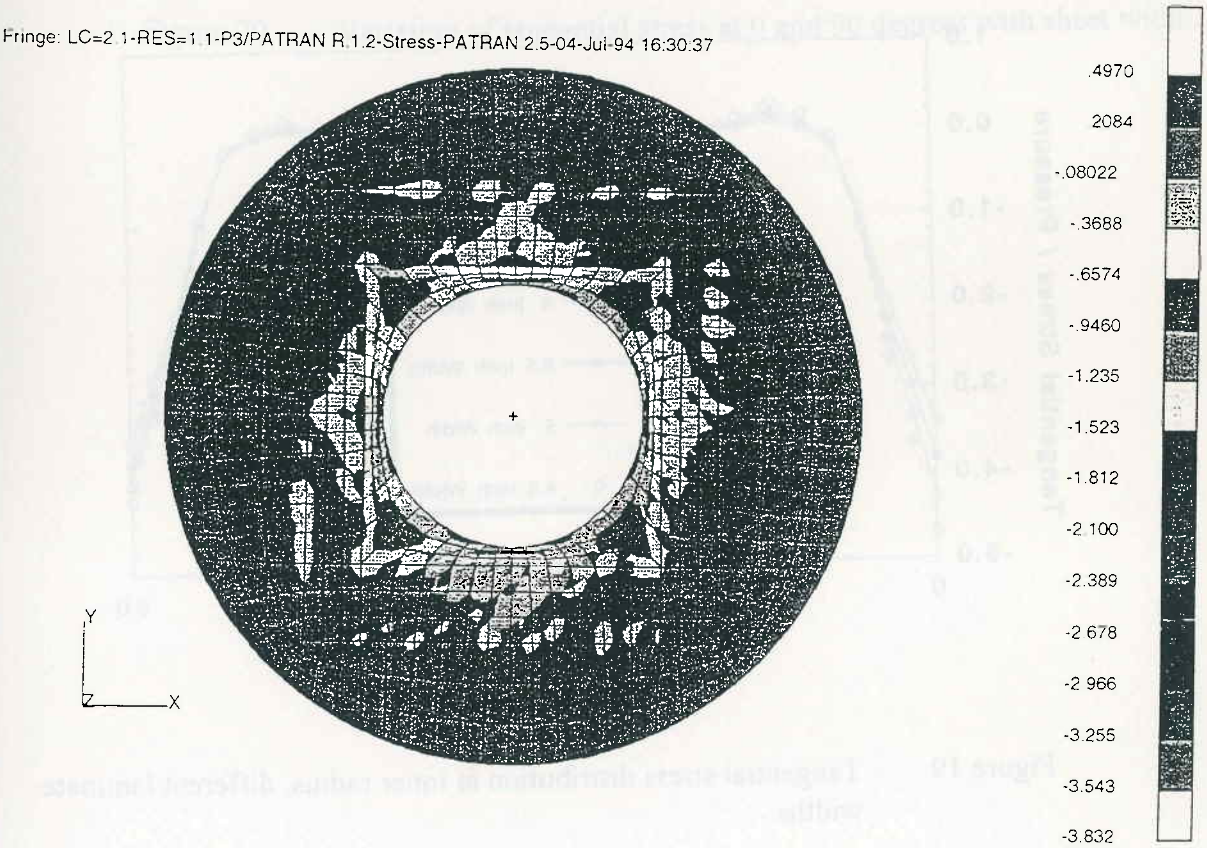

Figure 17 Contour plot for averaged tangential stress, quasi-isotropic sheet.

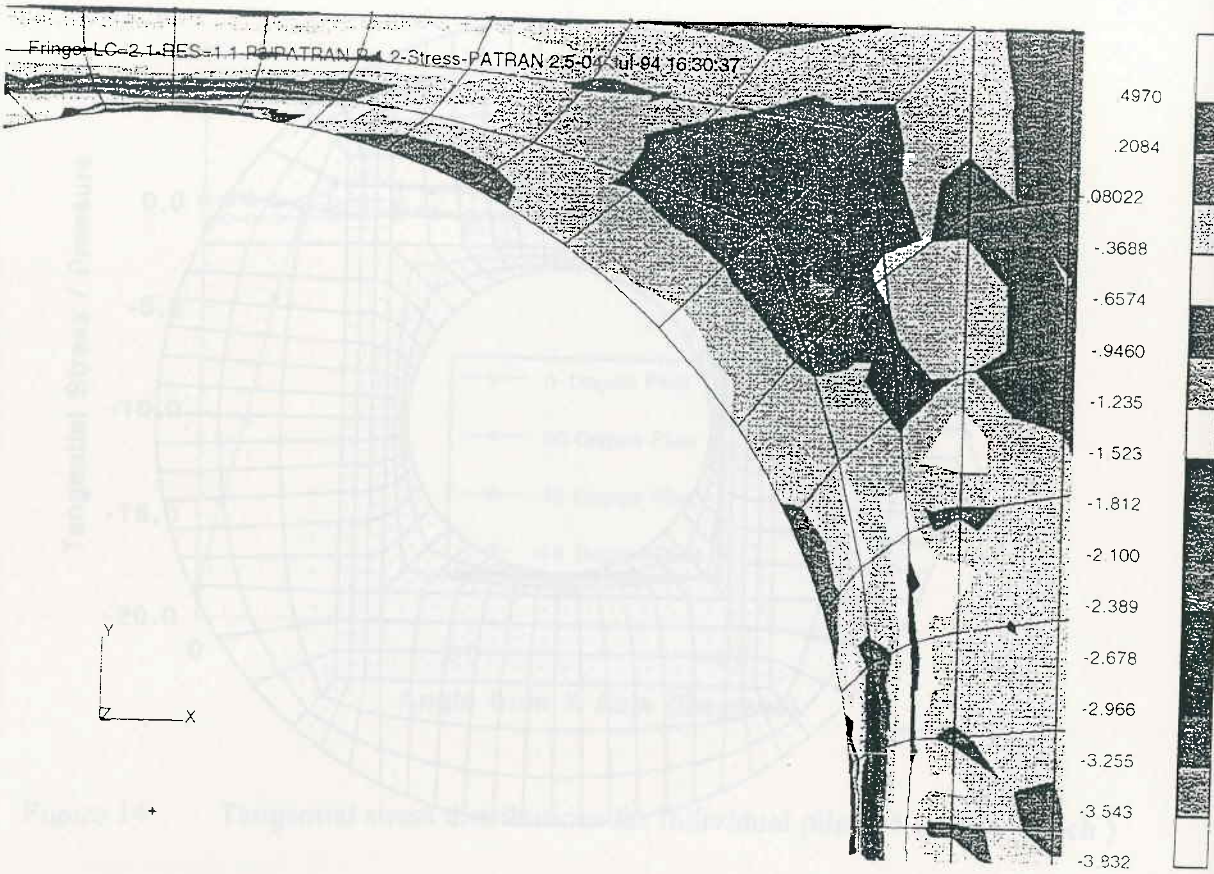

Figure 18 Region of contour plot near inner radius of model.

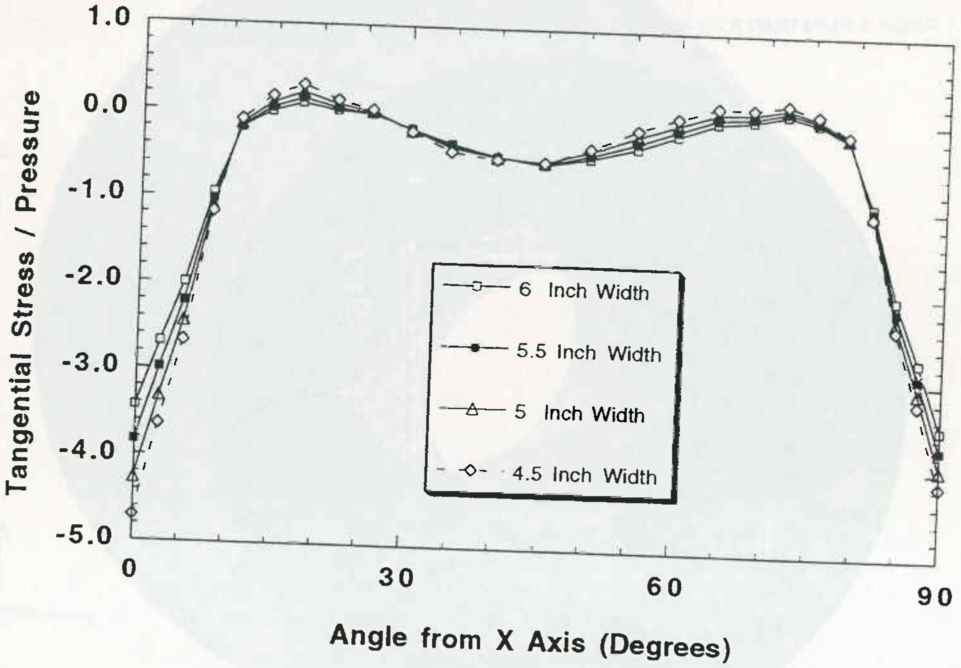

Figure 19 Tangential stress distribution at inner radius, different laminate widths.

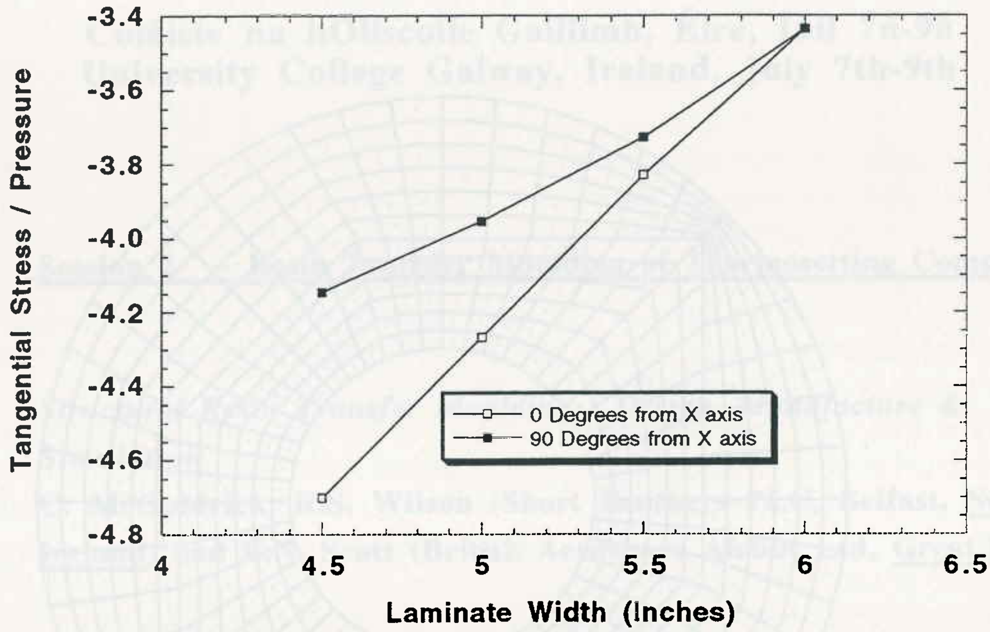

Figure 20 Variation of tangential stress at 0 and 90 degrees with sheet width.

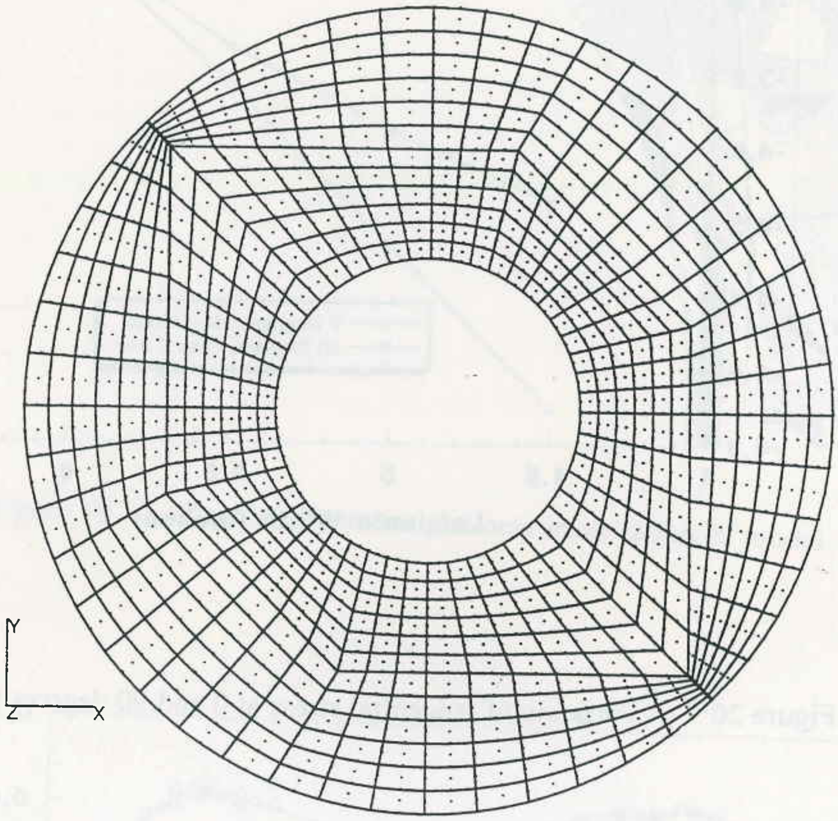

Figure 21 Mesh used to analyse 6 inch square laminate with corners cut off.