Design and Analysis of a Liquid Moulding Process for an Industrial Composite Structure.

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1 Abstract

Resin Transfer Moulding (RTM) is an important technique for producing industrial composite structures, in which liquid thermoset resins are used to infiltrate fibre preforms which have been prepositioned in a complex curvature mould. RTM is a versatile and attractive process for high volume, high performance and low cost manufacturing of polymer composites. The lower cost of composite production allows composites to be used for purposes hitherto thought of as wasteful.

In this paper the focus will be on the design of a composite roof beam to be used in areas unsuitable for conventional building materials, and also the design and construction of a mould for the RTM process. The optimum mould fill time for the complex mould, for different types and orientations of fibres, is investigated using a finite element package. The package uses a finite element control volume technique to predict the advancement of the flow front during mould filling. A two-dimensional version of Darcy's Law is used to describe the flow of the resin through the fibre mats. This is valid as the cavity thickness is small compared to the other dimensions of the component.

Mechanical tests were carried out on the roof beam to determine the properties, such as flexural modulus and strength of the final product. The results of mechanical tests are compared with those anticipated using finite element analysis of the beam design. An experimental rig was constructed to determine the validity of the LIMS analysis in practice.

2 Introduction

Resin Transfer Moulding (RTM) is a closed mould low pressure process which ideally suits the fabrication of large items of somewhat complex design. To date most interest in RTM has invariably come from the automotive and aeronautical industries, mainly due to the potential weight savings which could be achieved. Composite materials do of course have many other important properties which may be of use in many different industries, such as the construction industry. In this project we wish to design a Glass Reinforced Polyester beam to support a flat roof. The roof in question is the roof of a chemical settling tank, which by nature is a highly corrosive environment. RTM is ideally suited to the production of glass reinforced polyester beams, with quite high tolerances possible.

For RTM to be used effectively in any domain it must be understood, that is to say its process time and mechanical properties must be predictable and repeatable. The use of flow analysis will allow prediction of mould filling times. Liquid Injection Moulding Simulation (LIMS) [5] is the name of the package used for flow analysis. Potential problems such as trapped air can also be anticipated before a final mould design is decided upon. Mechanical properties are predicted with the use of a finite element analysis package called PATRAN [1].

3 Application

The RTM process in this case is used to create a closed end Glass Reinforced Polyester (GRP) C-beam. This beam is made in collaboration with Killarney Plastics, Ltd., Co. Kerry, Ireland. The C-beam was required to be used as a roof support beam for a large flat roofed settling tank. Figure 1 shows how the tank is assembled. The tank would at any time contain highly corrosive chemicals which would attack conventional building materials. The roof of the tank is made up of SMC panels which have dimensions 1.22m x 1.22m.

The thickness of the C-beam was decided upon once all the loads were taken into account. The main design loads were:

- A vacuum in the tank of 750 Pa
- A snow load of 765 Pa
- Each panel has a mass of 30 Kg
- The roof is designed to support two workmen and their tools i.e. 180Kg

Each beam must support the load of two panels. The total load is

Vac. load = 750 Pa = 75 Kg/m^2 = 112 Kg/panel = 224 Kg
Snow load = 765 Pa = 76.5 Kg/m^2 = 114 Kg/panel = 228 Kg

$\therefore$ Total load = 662 Kg
$\therefore$ Force on beam = 6494 N

This is the force which will be placed upon the beam. The beam has rigid supports since it is connected to the wall of the tank using 12 mm bolts. This information is used in the finite element analysis. A maximum deflection of less than 18 mm is required for the C-beam under the above force conditions.

4 Measurement of material properties

In order to run any computer analysis, such as flow or mechanical analysis, accurate material properties must be obtained which can be used as inputs in the analysis. The material properties with which we are concerned are the flow properties during production of the beam, and the material mechanical properties once the resin has cured.

4.1 Permeability measurement

A flat mould with a clear perspex top was constructed in order to measure the permeabilities for fabrics used in the RTM process, the clear perspex top was used so that the flow front may be observed and timed as it progresses through the fabrics. Figure 2 shows how the fabrics were laid up in the mould.The fluid is injected at a center gate and the progress of the flow front may be observed through the perspex top. An isotropic fabric (i.e. equal properties in all directions) should produce a circular flow front, orthotropy should produce an elliptical flow front. The permeability or permeabilities can be measured from the time taken for the flow front of the resin to travel a certain distance through the fabric.

Different fabrics and lay-ups were tested in the permeability rig. Both types of fabric are made by PPG Glass Fibres Ltd. The first type of fabric is a random chopped strand mat, the second is a continuous orthogonal weave. Firstly the fabrics were tested [2] using engine oil as a model fluid. Then a test under the same conditions as in the beam production i.e. gap height, volume fraction and the use of polyester resin was carried out. Results are shown (Fig. 3) for the permeabilities. The equation used [3] to calculate these results from the raw data is a modification of Darcy's law :

$$\frac{1}{2}\left(\frac{R}{r_0}\right)^2\left(\ln\left(\frac{R}{r_0}\right)-\frac{1}{2}\right)=P_i\frac{K_{rr}t}{\mu r_0^2}-\frac{1}{4}$$

where

R = average outer radius

r_0 = initial radius

P_i = inlet pressure

t = time from once the flow front has passed r_0

μ = viscosity

and

$$K_{rr}=\sqrt{K_{xx}K_{yy}}$$

where

K_{xx} = permeability in the x-direction

K_{yy} = permeability in the y-direction

x = distance travelled by the flow front in the x-direction

y = distance travelled by the flow front in the y-direction

and

$$K_{xx} = K_{yy}\frac{x^2}{y^2}$$

Figure 4 shows a rough outline of the type of elliptical shapes which were noted in the experiments. As can be seen from the results, there is quite a large scatter (up to 40%), even though the same set-up is used for each experiment.

4.2 Measurement of mechanical properties

A flat plate mould was constructed so that plaques could be produced using RTM, with a polyester resin, from which specimens could be cut out and tested. Mechanical properties are calculated using these specimens. Figure 5 is a comparison of modulii for the different fabrics. The difference in modulus of the woven fabric in the 1 and 2 direction should be noted.

The specimens produced in the flat plate mould were cut to the required size [4] and tested in tension in the INSTRON universal testing machine. Specimens were not taken from around the injection port due to the possibility of fibre wash in this region. The property data recorded is in turn used in the finite element analysis of the beam. The following table shows the mechanical properties for the two types of mat used, with all the modulii measured in GPa.

	E_{11}	E_{22}	G_{12}	V_{12}
Chopped strand random mat	**8.92**	**8.92**	**3.46**	**0.3**
Woven Fabric	**18.3**	**16.3**	**6.92**	**0.3**

Table

5 Finite Element Analysis

Finite element analysis is a very useful tool in design work. It allows the designer to create a computer model for the desired component. It is then possible to see what would happen if a certain load was applied at a point on the component. In this case two types of finite element analysis are required, mechanical and flow analysis.

5.1 Finite element flow analysis

In order to predict the fill time for the mould, also noting any possible filling problems, a control volume/finite element package called LIMS is used. This package which was developed at the University of Delaware in the USA uses a two-dimensional version of Darcy's law to describe the flow of resin through fibre mats. Darcy's law relates the flow rate to the pressure gradient, the fluid viscosity and the fiber bed permeability.

$$u = -\frac{K}{\mu}\nabla P$$

The first stage of the process was to see if LIMS would give an accurate solution to a simple problem. A model was made of the flat plate mould, inputting values of K_{xx} and K_{yy} which had previously been calculated. The results [2] agreed quite well with the experimental data. Now the package could be used for analysis of the C-beam mould.

Having already calculated the permeability of the mats being used, this data may be included in the program to give a computer simulation of the filling process. The version of LIMS does not include the effects of gravity on the mould filling process. Figure 6 is a display of the direction in which the flow front progresses. This may be seen in the short shots which were obtained by partially filling the mould. Picture No. 2 shows a beam which was partially filled with resin, note that the permeability was higher at the corners. This would have to be taken into account in further analysis.

Unfortunately when it came to the analysis of the C-beam the prediction for the mould fill time did not agree with the observed fill time. Several orders of magnitude differences were observed. At this preliminary stage, it is not possible to say what exactly was wrong. Further LIMS trials will be needed before any definite conclusion is drawn.

5.2 Finite element mechanical analysis

Finite element analysis was carried out on the beam in order to determine dimensions for the beam, so that it could carry the required load. This analysis is very important as it allows the user to design the mould in the knowledge that the beams produced from it will withstand the forces. Such analysis would be impractical to carry out without such engineering tools. To carry out the analysis a complete computer model of the beam was produced. Once the necessary loads and boundary conditions are applied to the model it may be analysed.

To obtain a solution for the laminate model the finite element package (PATRAN) uses Classical Lamination Theory [6] for which there are two basic assumptions:

1. The surface normals remain normal when the laminate deforms

$$\varepsilon_i = \varepsilon_i^0 + z\kappa_i \qquad i = 1,2,3 \qquad (1)$$

where ε_i is the strain, ε_i^0 is the midsurface strain, κ_i is the curvature and z is the distance from the neutral surface.

2. Each layer is in a state of plane stress, implying that the transverse stresses are all zero

$$\sigma_{33} = \sigma_{23} = \sigma_{31}$$

The constitutive equation for an orthotropic ply in a state of plane stress is given by

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{33} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix}$$

where

$$Q_{11} = \frac{E_{11}}{(1 - \nu_{12}\nu_{21})}$$

$$Q_{22} = \frac{E_{22}}{(1 - \nu_{12}\nu_{21})}$$

$$Q_{12} = \frac{\nu_{21} E_{11}}{(1-\nu_{12}\nu_{21})} = \frac{\nu_{12} E_{22}}{(1-\nu_{12}\nu_{21})}$$

$$Q_{33} = G_{12}$$

The constitutive matrix $[\overline{Q}]$ for a layer of the laminate frame is given by

$$[\overline{Q}] = [T]^T [Q][T]$$

with

$$[T] = \begin{bmatrix} \cos^2\theta & \sin^2\theta & 2\cos\theta\sin\theta \\ \sin^2\theta & \cos^2\theta & -2\cos\theta\sin\theta \\ -\cos\theta\sin\theta & \cos\theta\sin\theta & \cos^2\theta - \sin^2\theta \end{bmatrix}$$

where [T] is the matrix transforming the laminate frame strain into the ply frame and θ is the angle from the laminate frame to the ply frame (fig 7). Combining the expression for the kinematic assumption, (1), with the constitutive equation for the k^{th} ply

$$\{\sigma\}_k = [\overline{Q}]_k \{\varepsilon\}_k$$

yields

$$\{\sigma\}_k = [\overline{Q}]_k \{\varepsilon^0\} + z[\overline{Q}]_k \{\kappa\} \qquad (2)$$

substituting (2) into the integral expressions for force per unit length {N} and moment per unit length {M}

$$\{N\} = \int \{\sigma\} dz \quad \text{and} \quad \{M\} = \int \{\sigma\} z dz$$

The midsurface strains $\{\varepsilon^0\}$ and curvatures $\{\kappa\}$ are not a function of z, and $[\overline{Q}]_k$ is constant within each ply, so the above expressions may be simplified to

$$\{N\} = \{\varepsilon^0\} \sum_{k=1}^{n} [\overline{Q}]_k (h_k - h_{k-1}) + \frac{1}{2}\{\kappa\} \sum_{k=1}^{n} [\overline{Q}]_k (h_k^2 - h_{k-1}^2)$$

$$\{M\} = \frac{1}{2}\{\varepsilon^0\} \sum_{k=1}^{n} [\overline{Q}]_k (h_k^2 - h_{k-1}^2) + \frac{1}{3}\{\kappa\} \sum_{k=1}^{n} [\overline{Q}]_k (h_k^3 - h_{k-1}^3)$$

where h_k is the co-ordinate of the top of the k^{th} ply.

Figure 8 shows a plot of displacement under a load of 6 KN. The beam exhibits a greater deflection in the flanges due to the torsional effects. The web which carries most of the load deflects by a lesser amount. Figure 9 is a plot of the Von Mises stresses in the beam. The regions of higher stress are the regions at which failure is most likely to occur, i.e. under the loading point and at the supports.

6 Experimental procedure

Once the dimensions of the beam were decided upon the next stage was the production of a mould. It was decided that the most cost effective type of mould would be a glass reinforced polyester mould. The mould is constructed using a mixture of hand and spray lay-up with a coating of gel coat to give a smooth finish.

The same two types of glass fabric are used in the beam production, as were used earlier in the tests The beams are produced using a mixture of chopped strand mat and woven glass fabric. Polyester resin is the matrix material.

A HYPAJECT 6 MKII resin injection machine was used for the injection of polyester resin into a closed fibreglass mould, as can be seen in picture No. 1. The mould is held closed with the aid of clamps. To allow the air to escape a pinch-off method of sealing the mould is used, i.e. the fabric drapes over the end of the mould. When the mould is clamped the fabric is squeezed and since air has a much lower viscosity than resin, the air will be expelled before the resin. This method also enables us to know when the mould is full as there is a small amount of leakage through the pinch-off when all the air has been expelled.

As can be seen in Fig. 10 the beams were constructed with a web of 10mm, the ends and flange have a thickness of 7mm.The flange and ends are made up of either four layers of woven fabric mixed with six of random, otherwise the formation is two to eight in favour of the random mat. There are 4 extra layers of random fiber mat along the web. The woven glass fabric, though more expensive has higher mechanical properties, so a balance must be struck between the production cost and the desired weight of the beam. For this reason different lay-ups are used and the resultant beams are tested.

The beams are tested under central loading with the ends bolted to rigid supports (fig 11). Deflection is measured using a dial gauge on the underside of the beam. Axial strain is measured with the use of a strain gauge. On observation the beams tended to buckle before failure. The existing beams being used by Killarney Plastics (i.e. two 1.22m SMC beams bolted together) were also tested. These beams failed at the joints before severe torsional effects were noted.

7 Results

The modulus of the beams can be calculated using the plots of load against deflection (fig 13). The equation for calculating bending modulus [7] is

$$E = \frac{PL^3}{64Iv}$$

where v is the central deflection and the second polar moment of inertia of the beam $I = 21.657 \times 10^6$ mm^4. The modulus is therefore 4.875×10^9 Pa.

The strengths of the RTM beams are shown in comparison with the existing beams which are presently being used by Killarney Plastics in figure 12. A comparison between the beams using two (2wm) and four (4wm) layers of woven fabric along with the SMC beams (kill). The strength of the beam made with four layers of woven fabric was just higher than the one with two layers, with the existing SMC beams failing much earlier. Note should be taken of the fact that the SMC beams strength are based on catastrophic failure where as the RTM beam values were due to torsional instability.

A comparison of actual results of deflection is shown in fig 14. The actual results bear a good resemblance to those expected from PATRAN. This would imply that the method of Finite Element Analysis is valid for working with composite structures.

8 Conclusion

On analysis of the results it is clear that the beams produced by the RTM method are of sufficient strength to carry the load for which they are designed. The RTM beams have the advantage over the SMC beams in that bolts are not required to join the them. However production rate of the RTM beams is not expected to be as high as those produced by the press forming of the SMC beams. On the other hand equipment expenses for the RTM machinery and tooling is a fraction of the cost of those for press forming.

Taking all these things into account and the length of production run the RTM process shows all the signs of becoming an economically viable process in composite production.

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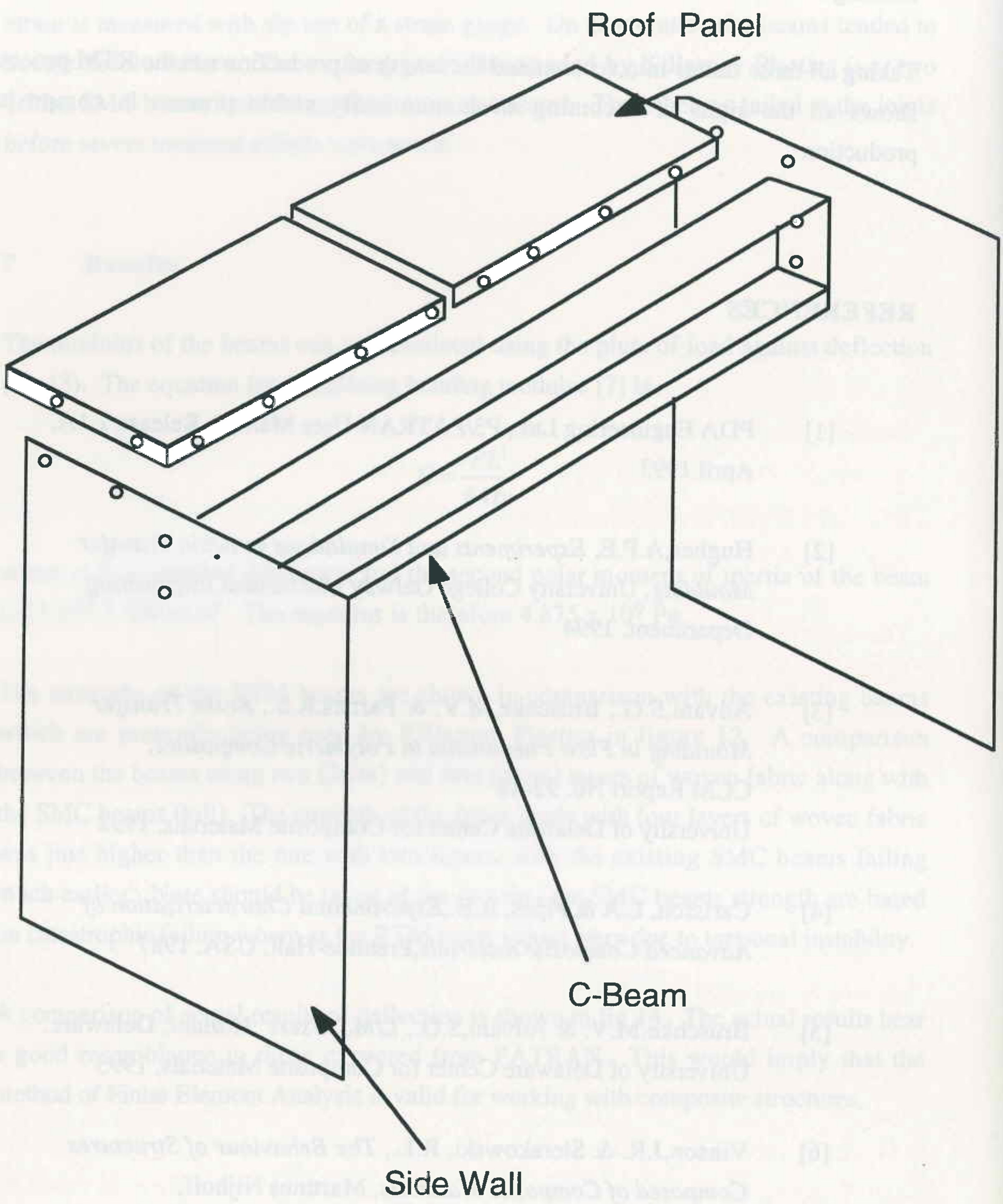

Figure 1 Schematic of the Tank Assembly

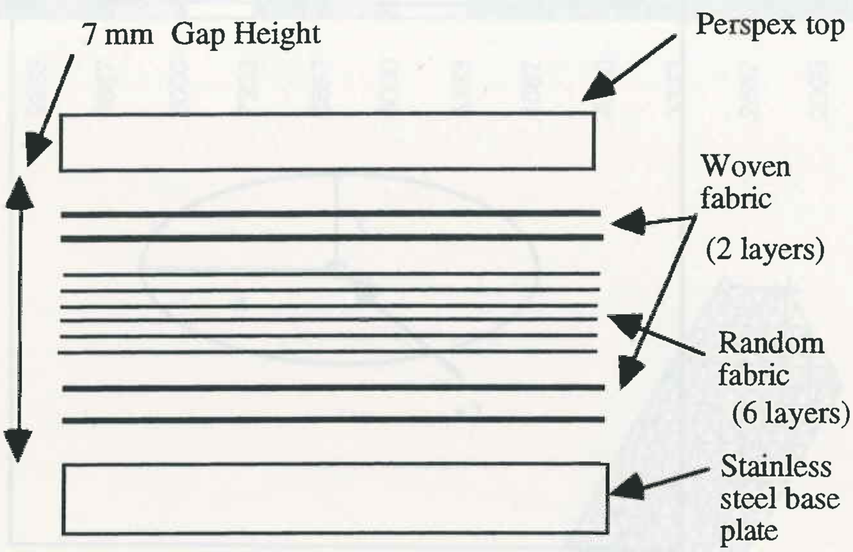

Figure 2 Lay-up of fabrics in the mould for measuring permeability

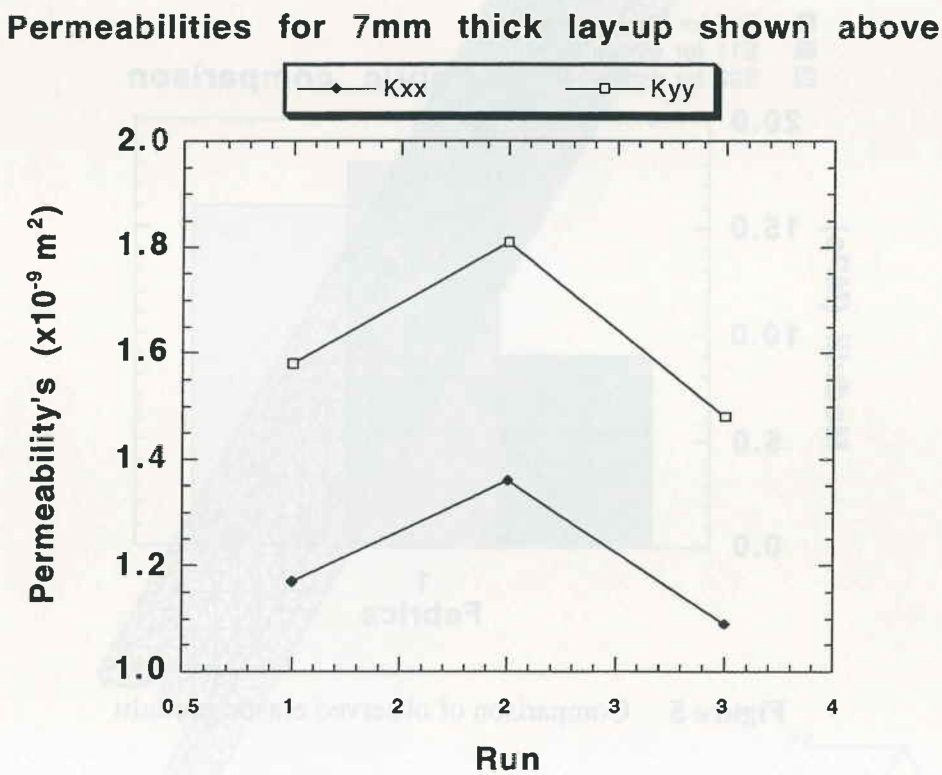

Figure 3 Graph of observed Permeabilities

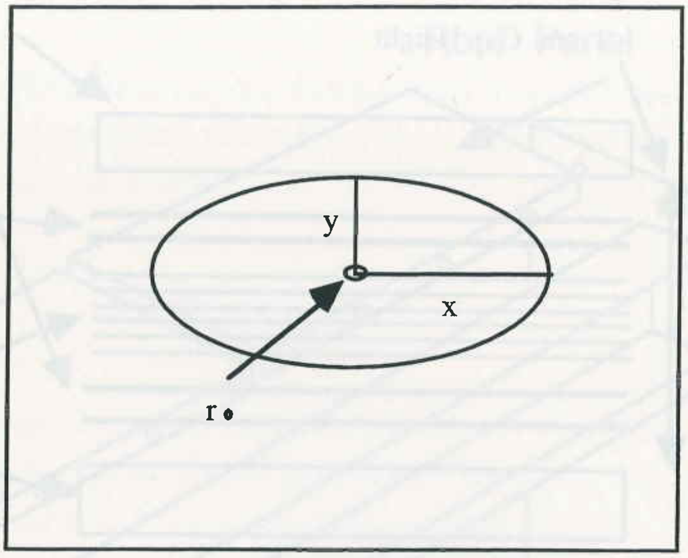

Figure 4 Elliptical shape of the flow front

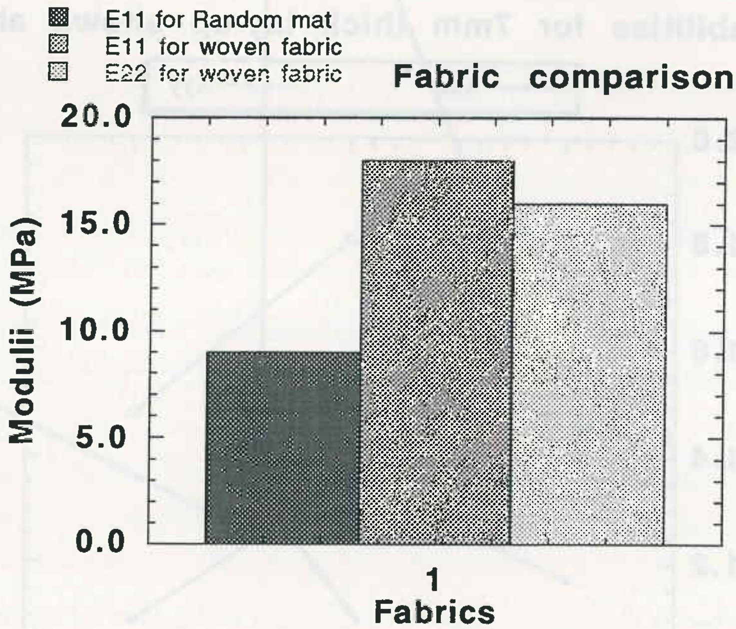

Figure 5 Comparison of observed elastic modulii

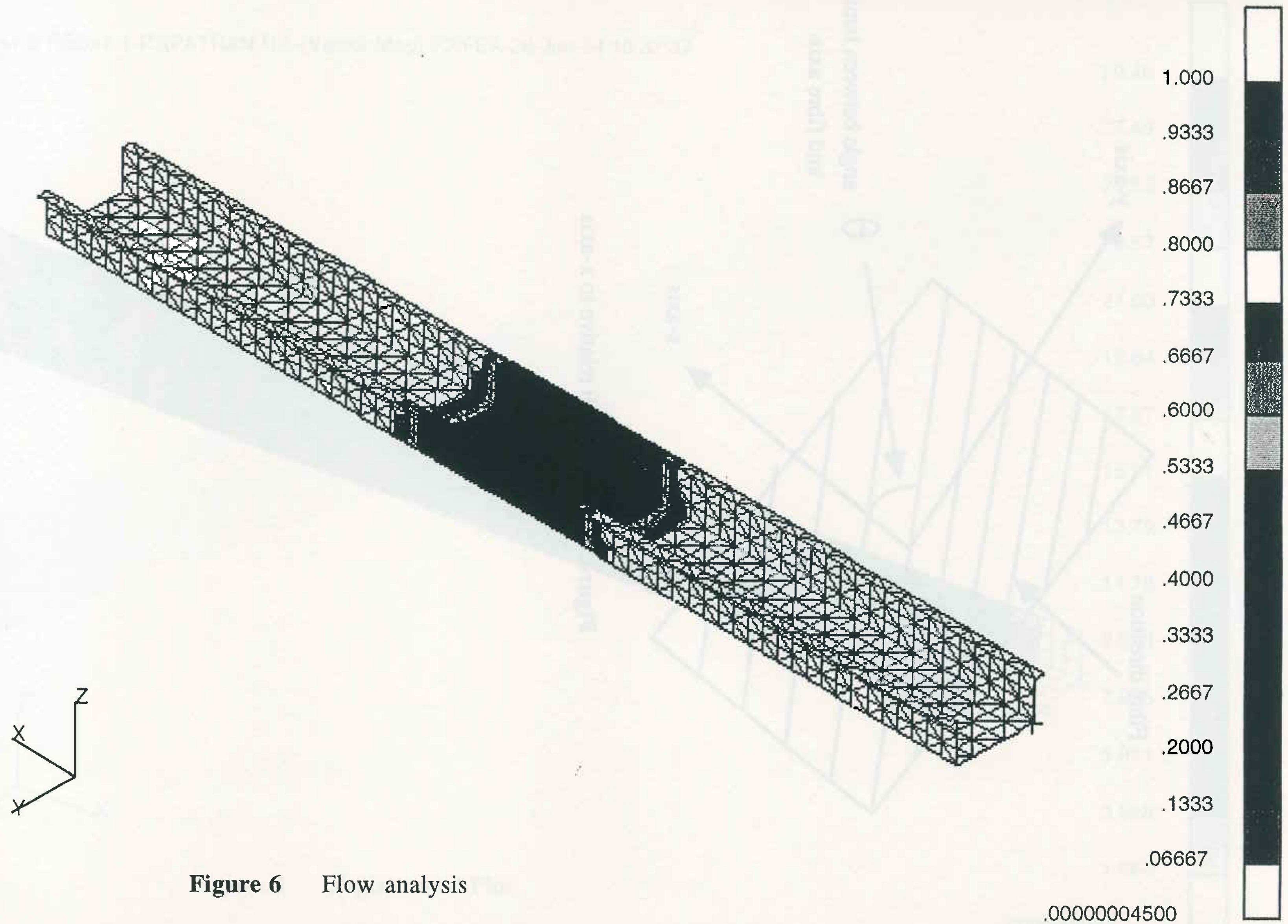

Figure 6 Flow analysis

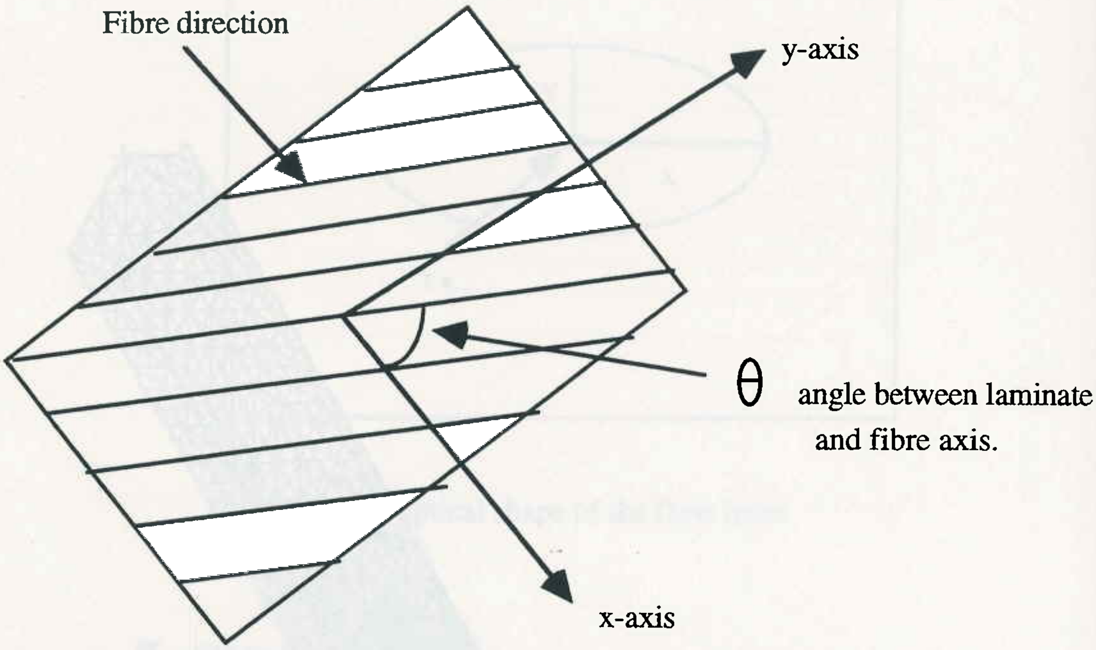

Figure 7 The angle θ relative to x-axis

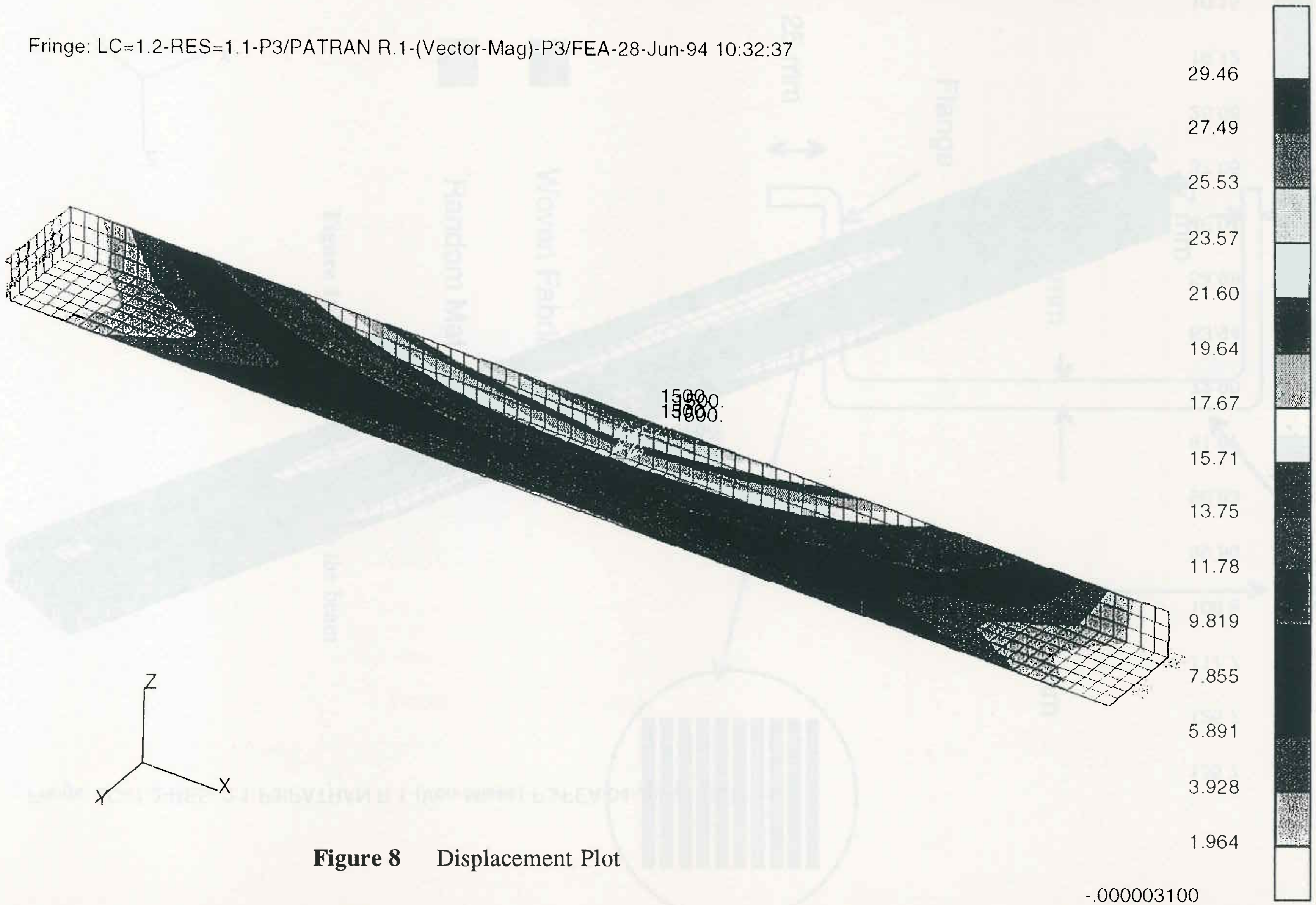

Figure 8 Displacement Plot

Figure 9 Von Mises stresses

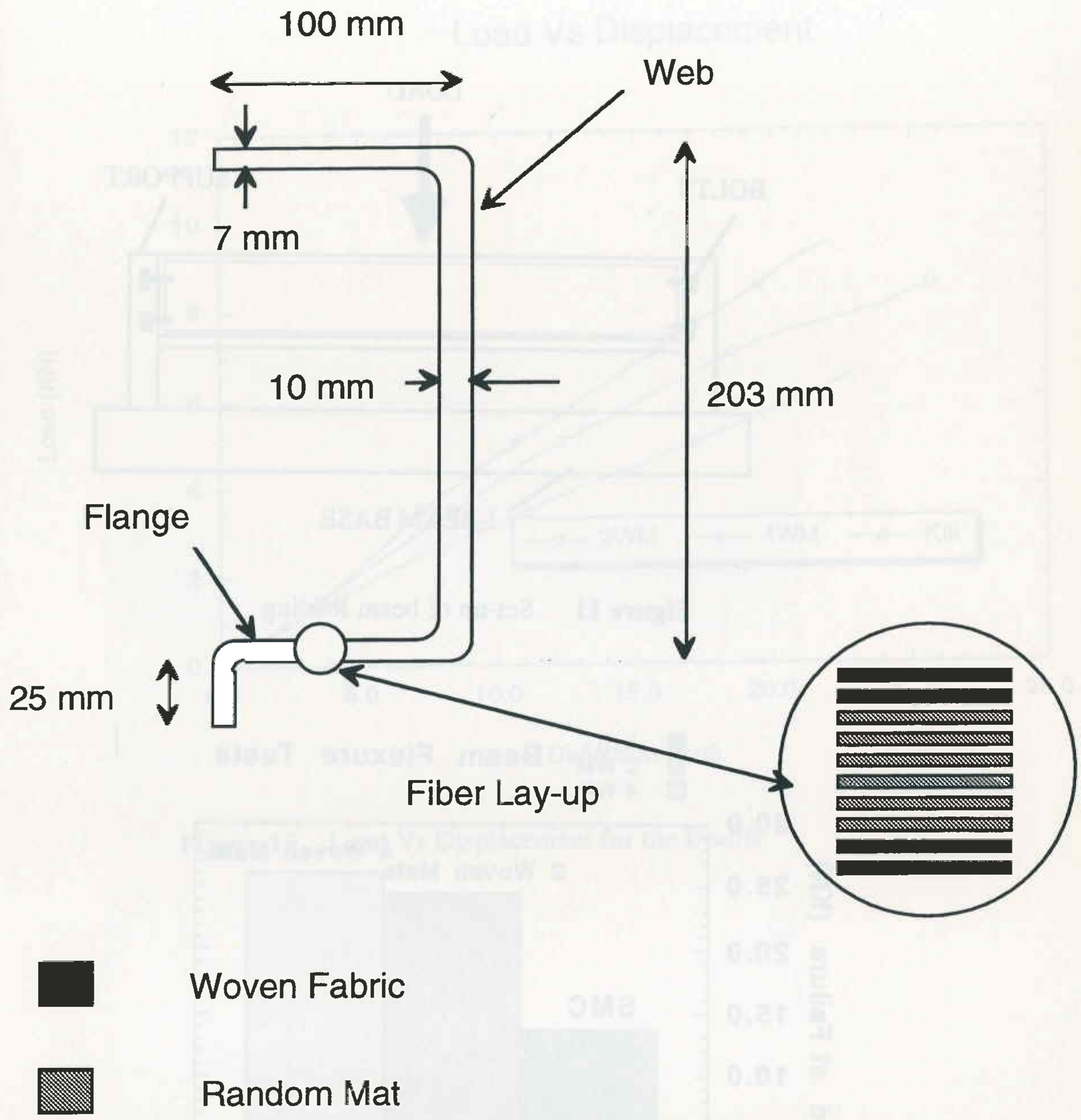

Figure 10 Cross section through the beam

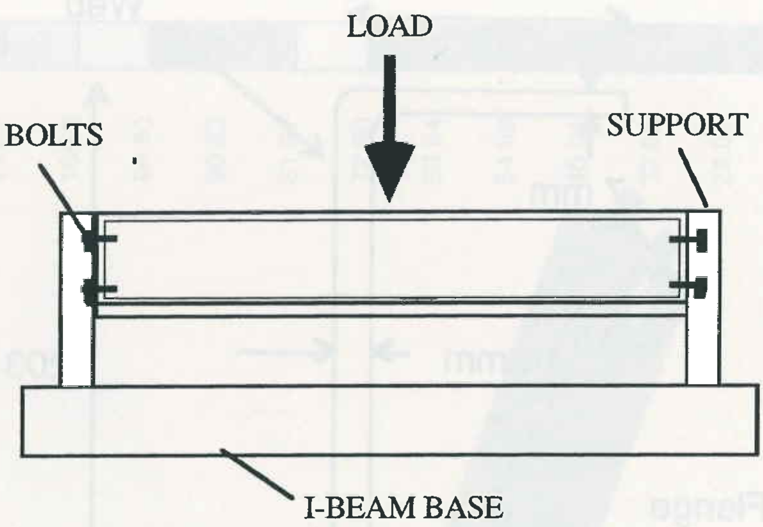

Figure 11 Set-up of beam loading

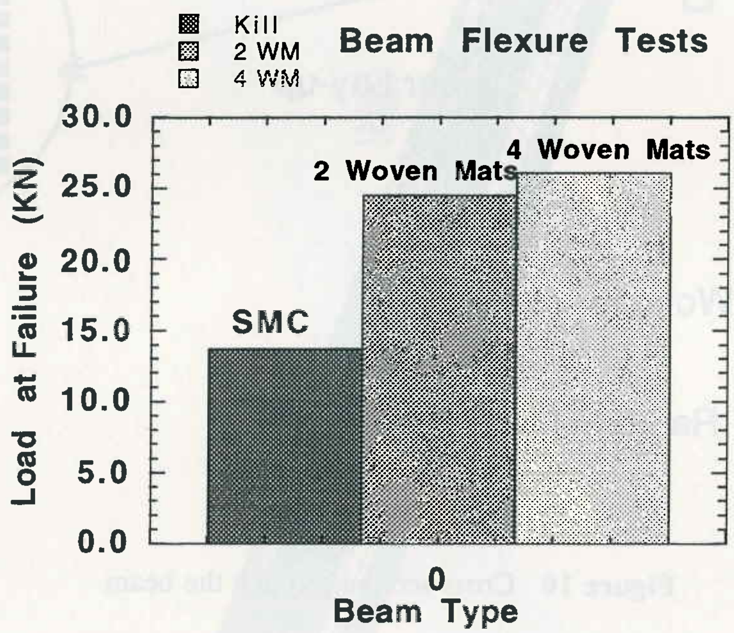

Figure 12 Comparison of failure strengths of different beams

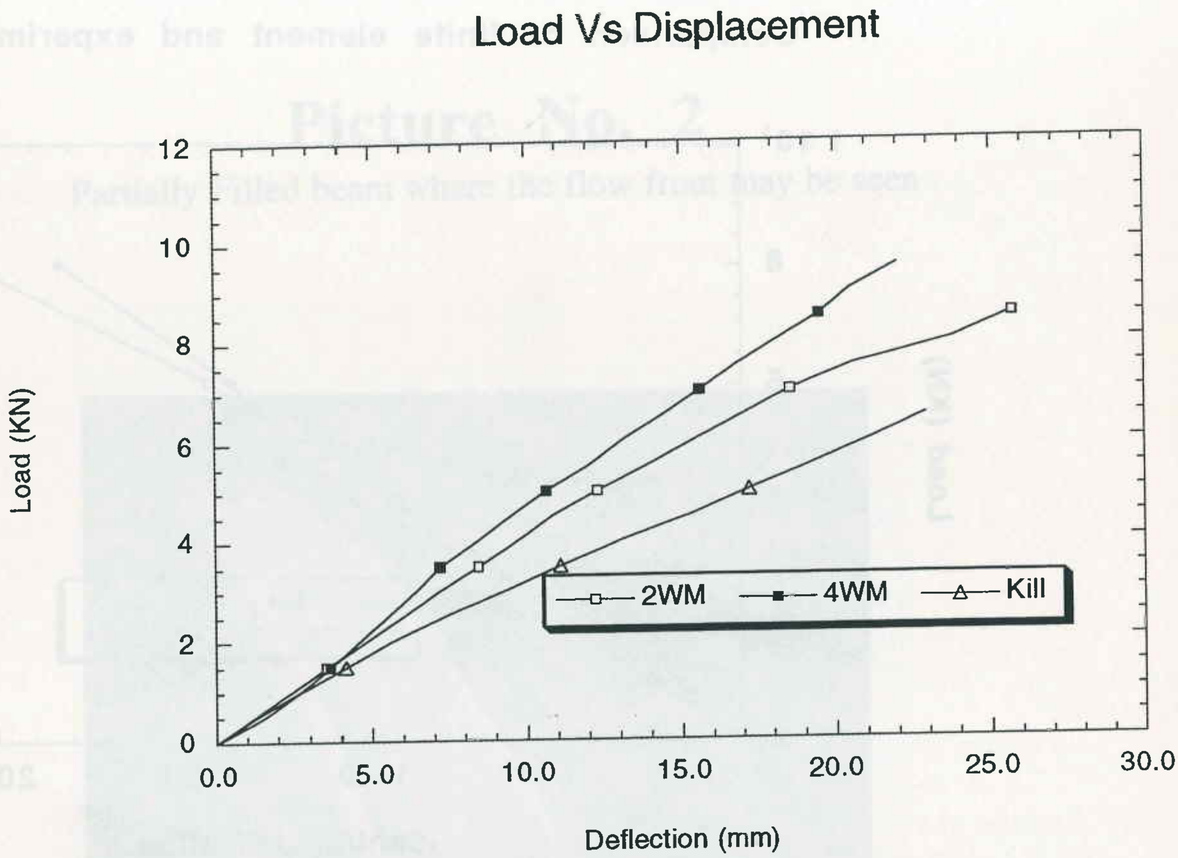

Figure 13 Load Vs Displacement for the Beams

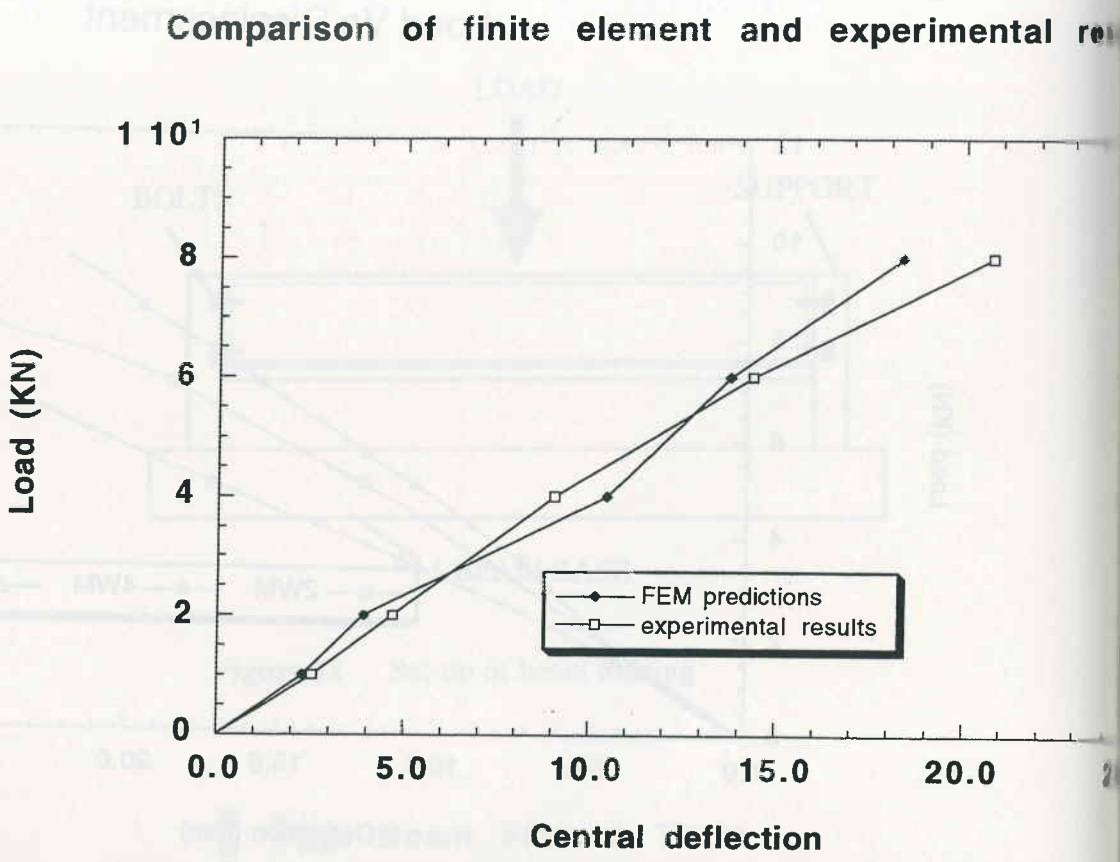

Figure 14 Comparison of actual and predicted results

Picture No. 2

Partially Filled beam where the flow front may be seen

Picture No. 1

RTM machine and the GRP mould during the injection process