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Design of a single fibre test specimen for normal loading of the interface

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Section:	Polymer Technology
Place:	Eindhoven University of Technology
Status:	Apprenticeship
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ACKNOWLEDGEMENTS

As a part of my study at the Eindhoven University of Technology, I did my first apprenticeship within the section of Polymer Technology under supervision of Dr. ir. Piet Schreurs.

The main object of this apprenticeship was to get familiar with fundamental research in general and the use of computers in specific.

During the first part of my apprenticeship, I worked together with Manolis Kyriakakis, who I would like to thank for the support and the good ideas he had concerning the tackling of the occurring problems. Also I would like to thank Piet Schreurs, who helped us whenever we had any problems. It was undoubtedly easier to understand his explanations than the cryptical ones written in the manuals.

This report will give an overview of the context of my apprenticeship, my work and possible directions for further research regarding this subject.

Gérard Vroomen

1. CONTEXT OF THE APPRENTICESHIP

In the section of Polymer Technology my apprenticeship was embedded in, one of the research topics is "Material Design".

For the development of materials with certain functional and/or mechanical properties, a detailed modelling and analysis of the microstructure is essential.

In composite materials the interface between fibre and matrix is a microstructural entity, which influences the macroscopic behaviour in a predominant manner. It is therefore important to determine its mechanical behaviour.

A lot of research is being done on the behaviour of the fibre-matrix interface while a shear stress is applied (pull-out tests for example). The goal of this apprenticeship was to analyze the behaviour of the fibre-matrix interface while loaded normally to the fibre.

2. GOAL OF THE APPRENTICESHIP

The goal of my apprenticeship was to:

"   Design, by using a finite element method, a single fibre test specimen shaped in such a way that it provides a uniform normal stress over a large part of the fibre-matrix interface. If time permits, try to extend the fibre-matrix configuration used in the analysis to a fibre-interface-matrix configuration. "

The finite element package used was MARC, combined with the pre- and postprocessor MentatII. The calculations were carried out on a Silicon Graphics computer.

3.   DESCRIPTION OF THE PROBLEM TO BE SOLVED

The problems occurring while trying to determine the normal strength of a fibre matrix interface are explained easily.

The normal strength can only be determined accurately if only normal stresses are applied to the interface. But, while loading the interface normally, the difference between the Young's modulus of fibre and matrix causes a difference in contraction.

As the matrix has a lower Young's modulus it will contract more than the fibre, which will result in shear stresses at the fibre-matrix interface and pressure in the fibre, as can be seen in fig. 3.1.

before loading   after loading

Fig. 3.1: shape of an ordinary test specimen before and after loading

To eliminate these stresses different approaches are possible. These approaches were simulated using the condition mentioned in the next chapter.

4.   CONDITIONS OF THE NUMERICAL ANALYSIS

4.1   Geometry

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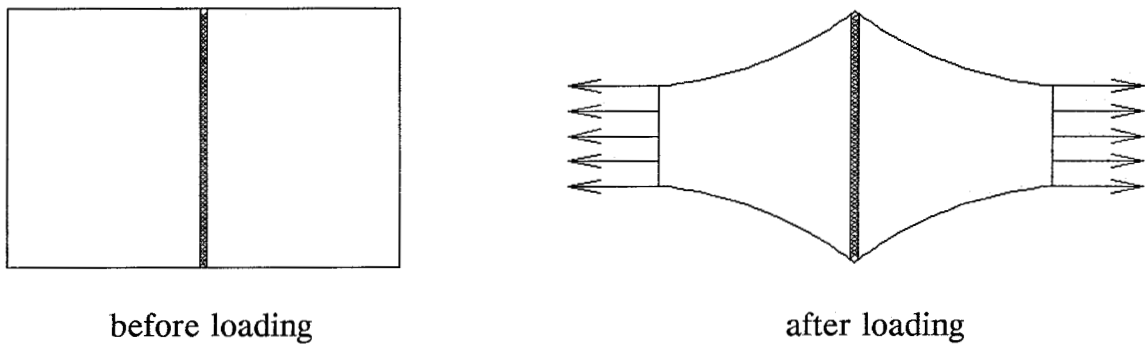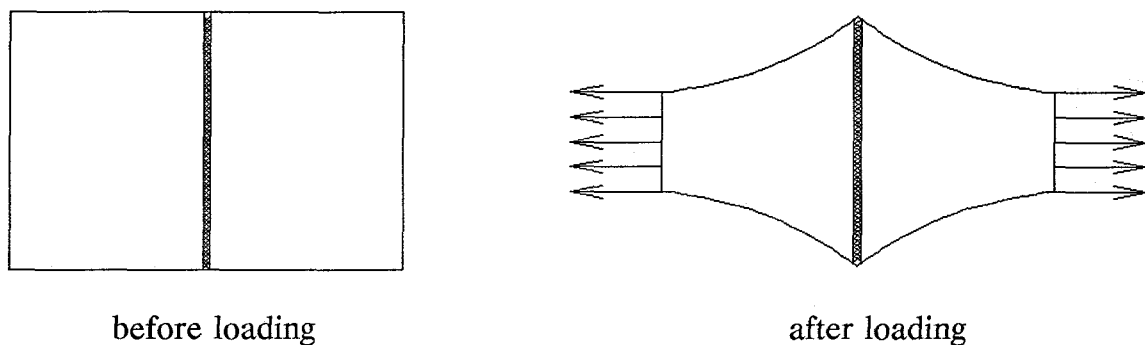

before loading   after loading

Fig. 3.1: shape of an ordinary test specimen before and after loading

To eliminate these stresses different approaches are possible. These approaches were simulated using the condition mentioned in the next chapter.

4. CONDITIONS OF THE NUMERICAL ANALYSIS

4.1   Geometry

A test specimen is a fairly flat piece of material and after loading, the interesting phenomenae occur within this plain. Therefore all numerical analysis was done using a 2-dimensional geometry. This way, the modelling of the test specimen was kept easy, which leads to results quickly. The thickness of the test specimen was made equal to the diameter of the fibre, 0.005 mm. Because a test specimen is such a flat piece of material without any restriction perpendicular to its plain, plain stress theory is presumed to apply.

Fig. 4.1: symmetry and set of coordinates

Due to two lines of symmetry only 1/4 of the test specimens needed to be modelled. This is shown in fig. 4.1.
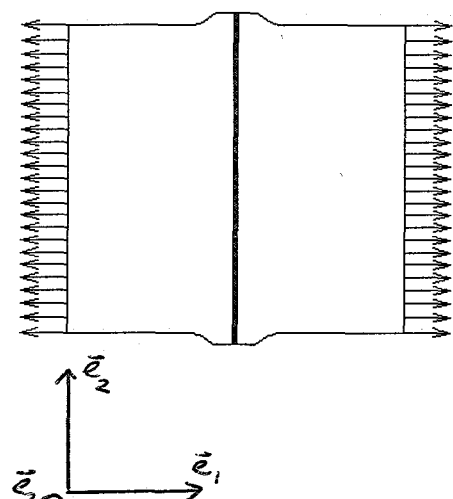
4.2   Material behaviour

Because this project was meant to present a brief overview of possible solutions, after which more detailed modelling could be introduced, only matrix and fibre material were modelled. During more detailed simulation a third material, the interface, could be modelled. Linear elastic material behaviour was presumed for both fibre and matrix.

4.3   Used elements

During the complete numerical analysis, quadratic plain stress elements were used. In MARC/MentatII, these elements are available as (3) plain stress quadrilateral.

4.4   Boundary conditions

Due to the symmetry fixed displacements were applied on two edges of the test specimens, corresponding with the lines of symmetry. Furthermore, on one edge (two edges occasionally) a normal edge load was applied. The fourth edge had either a fixed displacement, a normal edge load, no limitation at all or a combination of these three possibilities.

4.5   Used parameters

The following set of parameters has been used:

-	Young's modulus fibre:	200,000	N/mm^2
-	Contr. coeff. fibre:	0.3	
-	Young's module matrix:	3,000	N/mm^2
-	Contr. coeff. matrix:	0.3	
-	Diameter fibre:	0.005	mm
-	Applied edge load:	100	N/mm^2

Because of the linear elastic material behaviour, the value of the applied edge load is arbitrary. Doubling the load input leads to doubled stress and strain output. The value of 100 was used because it is an easy reference for the output values.

5. RESULTS OF DETERMINING THE APPROXIMATE SHAPE

5.1 Introduction

In order to comply with the goals set in Chapter 2, three solution were examined:
1) The introduction of a second fibre at the ends of the fibre to be tested. This fibre is supposed to lower the contraction of the matrix and to release the stresses near the ends of the fibre to be tested.
2) The introduction of cut-aways in one or two edges of the test specimen, to release the stresses at the ends of the fibre and the matrix surrounding the ends of the fibre.
3) The introduction of a bi-axial edge load in order to counteract the contraction.

These three solutions will be specified below. The figures show 1/4 of the specimen, the "top left" part, in the unloaded situation. The area of maximum stress is indicated in the figures. The level of the maximum stress, below the figures, is stated in N/mm^2.

5.2 The introduction of a blocking fibre

The first solution is to reduce the stresses at the ends of the fibre by putting fibres perpendicular to the tested fibre and thus blocking the ends as can be seen in fig. 5.1.
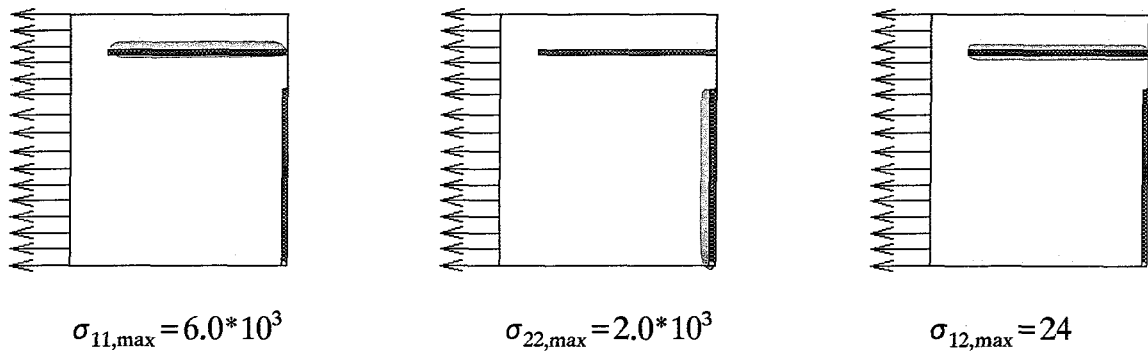

$$\sigma_{11,max} = 6.0 * 10^3 \qquad \sigma_{22,max} = 2.0 * 10^3 \qquad \sigma_{12,max} = 24$$

Fig. 5.1: 90° fibre block

As fig. 5.1 shows clearly, the stresses in the blocking fibre are much higher than the stresses in the fibre to be tested. Instead of solving a problem we have introduced another. The high stresses are caused by the condition of continuity, that forces the fibre to elongate as much as the matrix nearby. This effect can be diminished by putting a blocking fibre at an angle to the edge load. The results are shown in fig. 5.2.
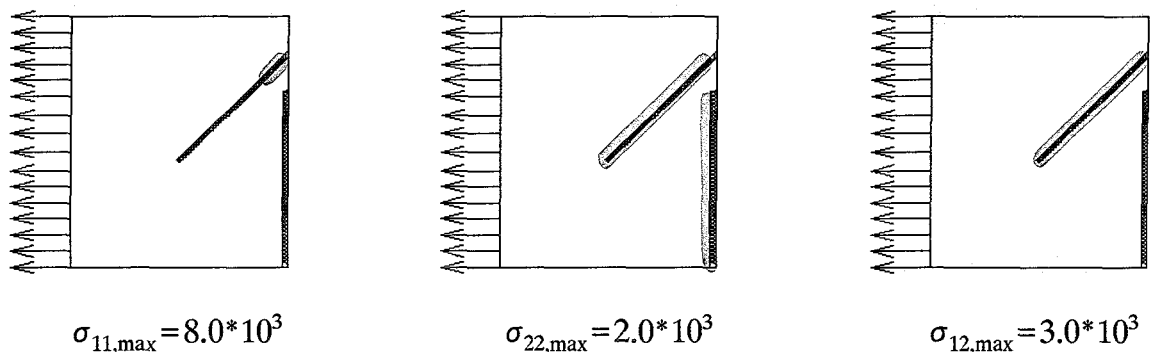

$$\sigma_{11,max} = 8.0 * 10^3 \qquad \sigma_{22,max} = 2.0 * 10^3 \qquad \sigma_{12,max} = 3.0 * 10^3$$

Fig. 5.2: 45° fibre block

The stresses in the fibre are indeed lower, but the sharp turn of the blocking fibre causes high stresses. Also, the σ_{12} stresses along the fibre have increased considerably. To determine whether or not a blocking fibre can be effective at all, a simulation was done, using a circular blocking fibre to avoid (sharp) edges. Besides the fact that it is not a realistic configuration, it isn't a solution either, as can be seen in fig. 5.3.
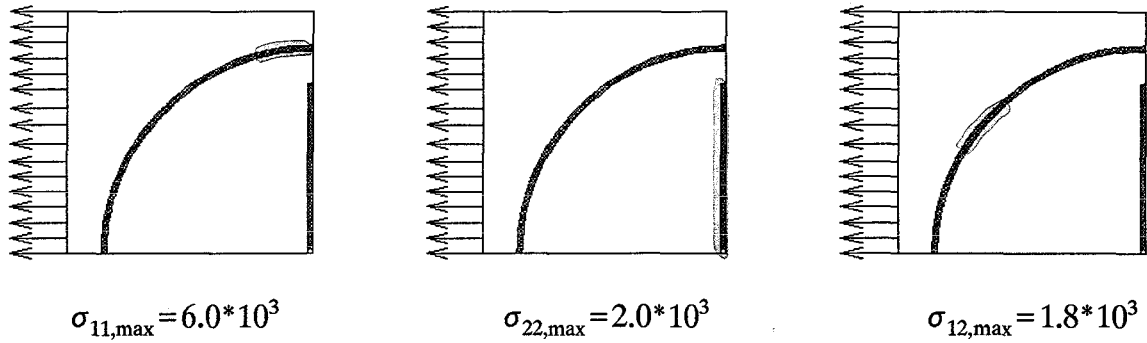
$$\sigma_{11,max} = 6.0*10^3 \qquad \sigma_{22,max} = 2.0*10^3 \qquad \sigma_{12,max} = 1.8*10^3$$

Fig. 5.3: circular fibre block

The blocking method could be used for low stress loading, but if the strength of the interface needs to be determined, the method isn't effective because the blocking fibre will break before the interface does.

5.3 The introduction of cut-aways

Another way to lower the stresses at the edges of the fibre is to make a cut-away, for example as shown in fig. 5.4.
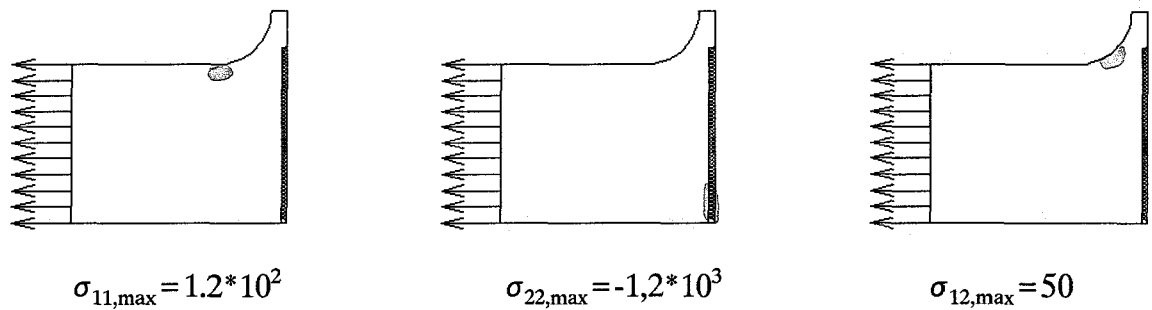
$$\sigma_{11,max} = 1.2*10^2 \qquad \sigma_{22,max} = -1,2*10^3 \qquad \sigma_{12,max} = 50$$

Fig. 5.4: deep wide cut-away

The σ_{11} stress is reduced effectively, as is the σ_{12} stress. The σ_{11} stress is still relatively high in the fibre and negative. This could cause buckling and can be converted into tension by introducing a fixation as shown in fig. 5.5.
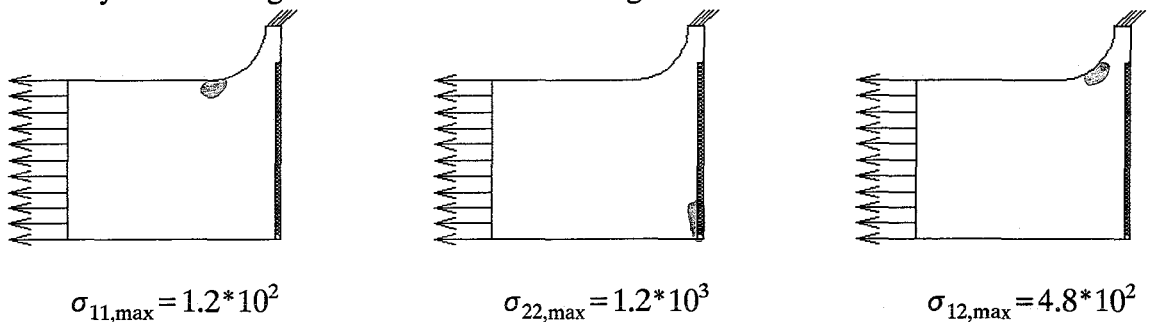
$$\sigma_{11,max} = 1.2*10^2 \qquad \sigma_{22,max} = 1.2*10^3 \qquad \sigma_{12,max} = 4.8*10^2$$

Fig. 5.5: deep, wide cut-away with fixation

Now, tension exists in the fibre. This could be an advantage, as the breaking of this fibre, somewhere during the experiment, could be a calibration for the determination of the stress levels. However, shear stresses in the corner of the cut-away are intolerably high. Therefore, a smoother cut-away was modelled as shown in fig. 5.6.
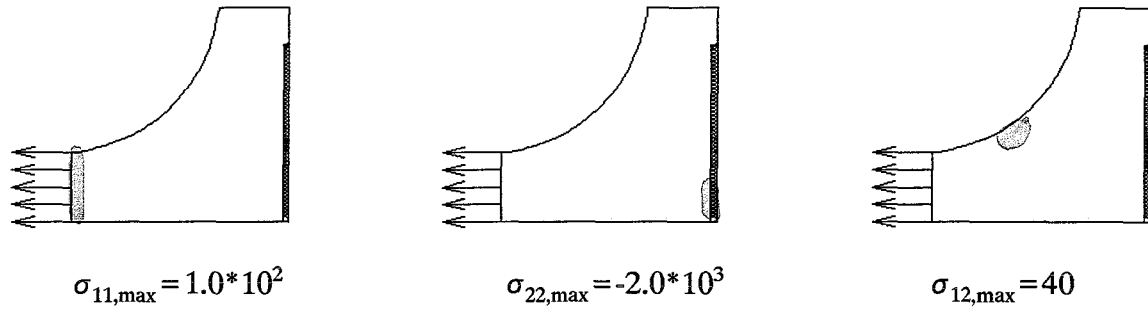

$$\sigma_{11,max} = 1.0*10^2 \qquad \sigma_{22,max} = -2.0*10^3 \qquad \sigma_{12,max} = 40$$

Fig. 5.6: large circular cut-away over 70% of the edge

Unfortunately this larger cut-away decreases the area of uniform normal stress.

Because a lot of problems seem to occur due to the fibre edges, a full length fibre test specimen was analyzed. The results are shown in fig. 5.7.
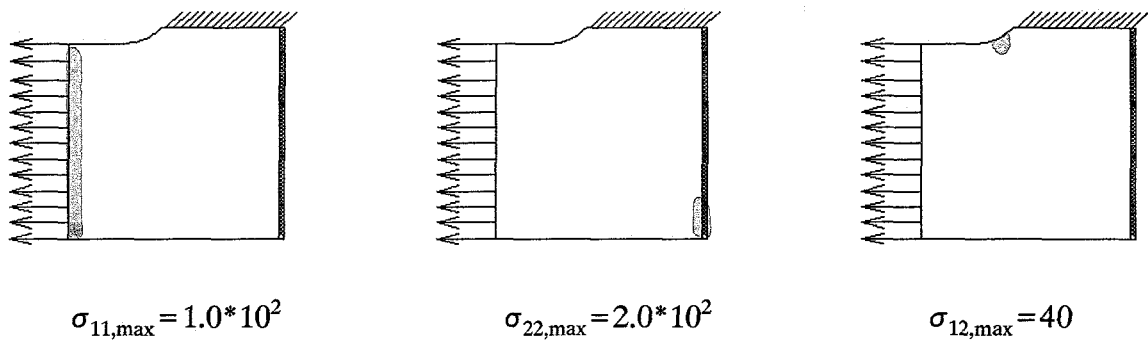

$$\sigma_{11,max} = 1.0*10^2 \qquad \sigma_{22,max} = 2.0*10^2 \qquad \sigma_{12,max} = 40$$

Fig. 5.7: full length fibre test specimen with undeep, narrow cut-away

The σ_{11} stress is uniform along the fibre, only the σ_{12} stress is a bit too high.

5.4 The introduction of a bi-axial edge load

The last solution which was modelled was to compensate the contraction by applying an edge load parallel to the fibre. Because of the contraction coefficients of 0.3 an edge load of 30% of the normal edge load was tried as shown in fig. 5.8.
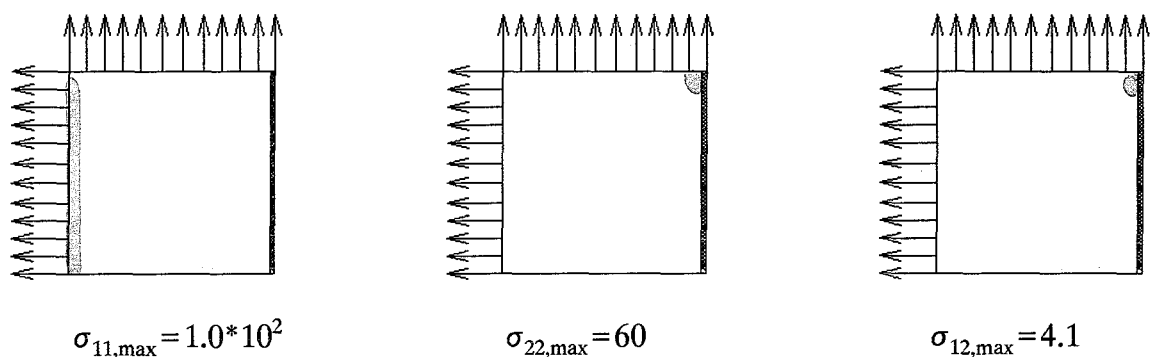

$$\sigma_{11,max} = 1.0*10^2 \qquad \sigma_{22,max} = 60 \qquad \sigma_{12,max} = 4.1$$

Fig. 5.8: bi-axial tension, no cut-aways

6. OPTIMISATION OF THE "CUT-AWAY" SHAPE

In the previous chapter, it was shown that a good solution can be found if edge loads in two directions can be applied. If not, something like the shape of fig. 5.7 must be used. Overall it is clear that the full length fibre test specimen offers the largest potential. Therefore the full length fibre test specimen with cut-away will be examined closer in this chapter.

Different shapes of cut-away were modelled, leading to an "optimised" shape. The σ_{11} stress was never intolerably high, therefore $\sigma_{11,max}$ isn't listed any more. The $\sigma_{11,mid}$ and $\sigma_{11,half}$ represent the stress in the middle of the fibre and the stress halfway the middle and the edge of the fibre, as can be seen in fig. 6.1. These two stresses show the level of uniformity of the normal stress at the fibre-matrix interface. Also two σmaximum second components of stress are listed. They represent the maximum stresses in the fibre and the matrix

Fig. 6.1: points of measurement $\sigma_{11,mid}$ en $\sigma_{11,half}$

At first, a cut-away out of the side edge was modelled, as can be seen in fig. 6.1.
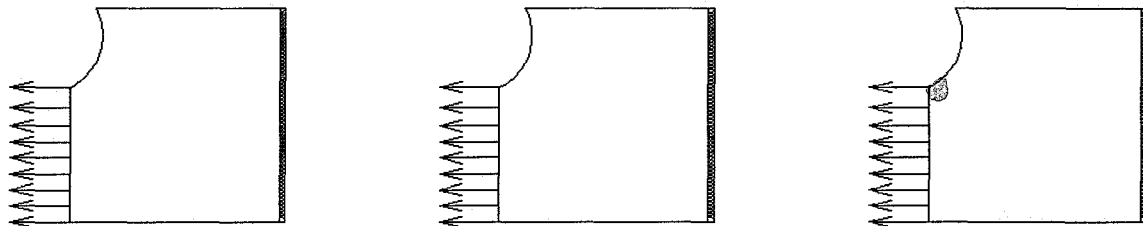
$$\sigma_{11,mid} = 90$$
$$\sigma_{11,half} = 70$$

$$\sigma_{22,max,fi} = 2.4*10^3$$
$$\sigma_{22,max,m} = -10$$

$$\sigma_{12,max} = 40$$

Fig. 6.1: side edge cut-away

Unfortunately the area of uniformity of the σ_{11} stress is small. Therefore an upper edge cut-away was analyzed, as is shown in fig. 6.2.
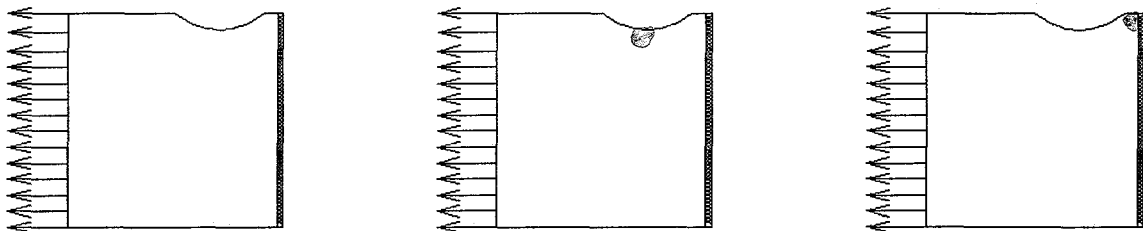
$$\sigma_{11,mid} = 1.0*10^2$$
$$\sigma_{11,half} = 1.1*10^2$$

$$\sigma_{22,max,fi} = -2.0*10^3$$
$$\sigma_{22,max,m} = 20$$

$$\sigma_{12,max} = 16$$

Fig. 6.2: upper edge cut-away

The uniformity of the σ_{11} stress is better than in the case of a side edge cut-away.

To further lower the σ_{12} a shape as can be seen in fig. 6.3 was modelled.

$$\sigma_{11,mid} = 1.0*10^2$$
$$\sigma_{11,half} = 1.0*10^2$$

$$\sigma_{22,max,fi} = -2.0*10^3$$
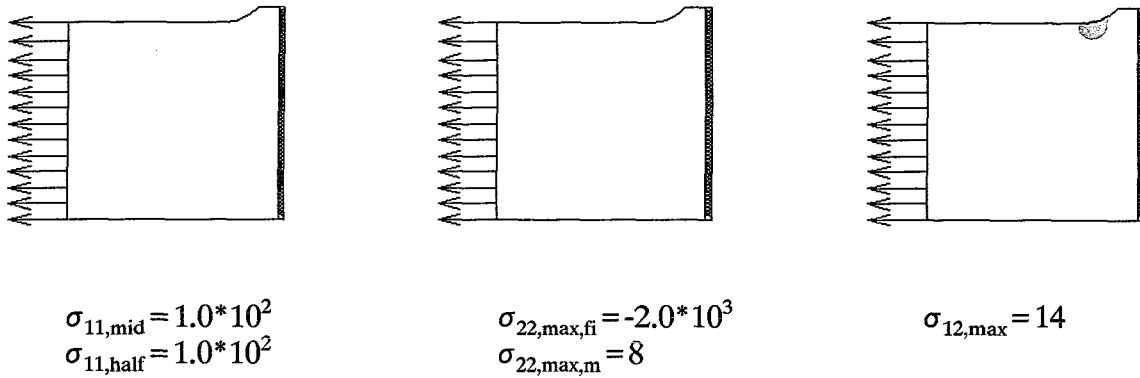$$\sigma_{22,max,m} = 8$$

$$\sigma_{12,max} = 14$$

Fig. 6.3: undeep (8% of the edge length), wide cut-away

The uniformity of the σ_{11} stress has also improved. The only problem that could still occur is the buckling of the fibre as pressure still exists in the fibre. Therefore a fixation was analyzed as can be seen in fig. 6.4.
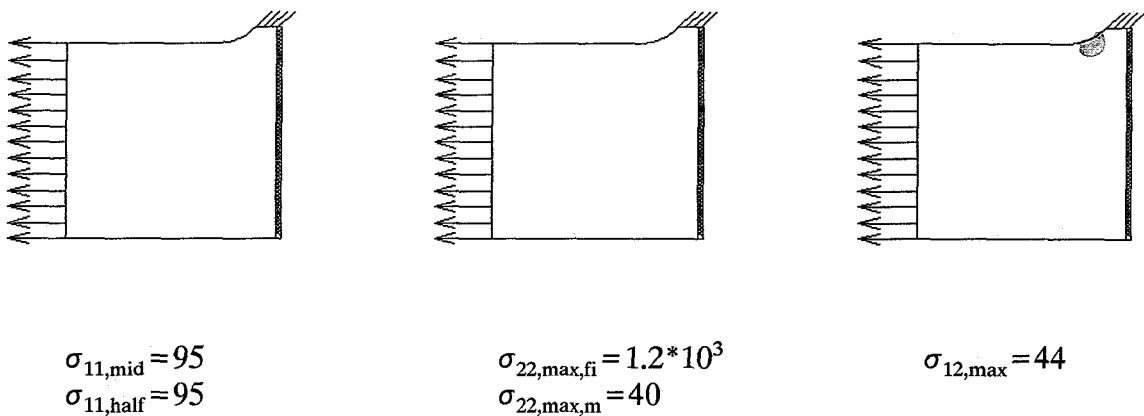
$$\sigma_{11,mid} = 95$$
$$\sigma_{11,half} = 95$$

$$\sigma_{22,max,fi} = 1.2*10^3$$
$$\sigma_{22,max,m} = 40$$

$$\sigma_{12,max} = 44$$

Fig. 6.4: undeep (8%), wide cut-away, fixation

This leads to tension in the fibre which could be useful as the breaking of the fibre is an indication for the stress-levels within the test specimen. A narrower cut-away leads to higher values for the σ_{12} stress as can be seen in fig. 6.5.

$$\sigma_{11,mid} = 93$$
$$\sigma_{11,half} = 94$$

$$\sigma_{22,max,fi} = 4.0*10^3$$
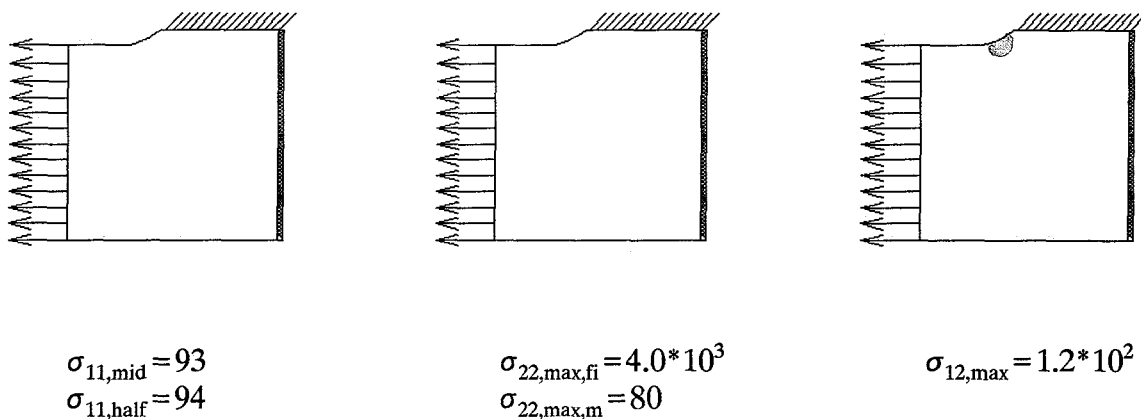$$\sigma_{22,max,m} = 80$$

$$\sigma_{12,max} = 1.2*10^2$$

Fig. 6.5: undeep (8%), narrow cut-away, one directional tension, fixation

It is clear that fig. 6.3 and fig. 6.4 represent a fairly good shape. If only a strictly one dimensional test is possible, the test of fig. 6.3 should be used. If fixation is possible and breaking of the fibre is useful, the configuration of fig. 6.4 is the best solution.

7. POSSIBILITIES FOR INTRODUCING INTERFACE ELEMENTS

In order to get a better agreement between simulation and experiment, it might be advantageous to take the fibre-matrix interface into account. This interface is the part of the specimen that is described correctly by neither the fibre parameters nor the matrix parameters.

There are roughly two options for introducing the interface in the simulation. The first option is to introduce a third material in between fibre and matrix with modified properties which describe the behaviour of the interface correctly. This behaviour is expected to be non-linear and non-elastic and some kind of a failure mode will have to be introduced for a correct description.

The second option is to define springs in between fibre and matrix. The stiffness of these springs then needs to be defined incorporating the features mentioned at the first option.

The time span of this apprenticeship was not long enough to try the options mentioned above thoroughly. The principle of the first option was tried and proved to be possible, if the correct material parameters could be determined.

Further research in this area is recommended.

8. CONCLUSIONS

- It is possible to shape a single fibre test specimen in such a way that uniform normal stresses over a considerable part of the fibre matrix interface occur.

- It is possible to test the specimen in a way that satisfies the demands as put down in the description of the goal. This is by applying a bi-axial edge load as shown in fig. 5.8. In this case, a test specimen without any cut-aways needs to be loaded with an edge load of 30% of the normal edge load in order to obtain optimum results.

- Using the right shape of cut-away, a test specimen can be made that reaches the goals with loading in only one direction. These simulations are shown in fig. 6.3 and fig. 6.4. The difference between these two simulations is that one (fig. 6.3) is strictly one-dimensional, whereas the other (fig. 6.4) has a fixation of the fibre in the direction of the fibre which could be useful if breaking of the fibre is desirable.