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Deep Drawing of Fabric Reinforced Thermoplastics
Simulation and Experiment.

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ABSTRACT

Deep drawing of fabric reinforced thermoplastics is a promising process for thin walled composite products. At the Delft University of Technology the process as well as two process simulation computer programs are being developed. The first program is based on a geometrical description method, the second program is based on a finite element method. In this paper some interesting results of the experimental process and the simulations are discussed.

INTRODUCTION

Deep drawing of fabric reinforced thermoplastics is an interesting option for the production of thin-walled composite products. The process is fast, clean and generally simple.

Unlike metals the formability of fabric reinforced thermoplastics does not depend on the plasticity of the material. On the contrary, it depends primarily on the draping characteristics of the applied fabrics. The main problem related with draping of a fabric is the prevention of buckling of its fibres since buckling may result in unwanted folds in the final product. It is therefore important to know in advance where problems during the draping may occur and how these problems, if any, can be solved.

In the Structures, Materials and Production Laboratory of the Faculty of Aerospace Engineering of Delft University of Technology the deep drawing process of reinforced thermoplastics is being developed. Several interesting results have already been obtained. It was shown, for instance, that the original orientation of the fabric relative to the mould is of paramount influence on the quality of the product, especially with regard to the appearance of wrinkles.

Parallel with the production process, two computer programs are being developed in order to simulate the draping of fabrics over surfaces of a more or less arbitrary shape. In this paper these programs are discussed briefly and some of the preliminary results are compared with results from the experimental deep drawing process.
1 DEFORMATIONS OF FABRIC.

During deep drawing of an impregnated fabric several modes of deformation may occur:
1. Fibre stretching.
2. Fibre straightening and related warping.
3. Shear Slip.
4. Deformation due to the trellis effect.

These modes of deformation are of different relevance for the simulation programs.

1.1 Fibre stretching (Fig 1a)

Fibre stretching due to a pulling force is of minor importance during deep drawing of fabrics. The ultimate strain of the fibres is about 1%, whereas the maximum displacements during the deep drawing process yield strains of about 35%. Fibre stretching has not been considered in the geometrical program for the deformation of fabrics. In the finite element program it has been taken into account, since it can give information about tension and compression zones which occur during the deep drawing process.

1.2 Fibre straightening and fibre warping (Fig 1b)

Fibre straightening causes warping of the fibres in the direction perpendicular to the straightened fibres. In woven fabrics, however, fibres are used in the form of relatively flat bundles and the effects of fibre straightening and fibre warping are small. They are not included in the simulation programs.

1.3 Shear slip (Fig 1c)

The deformation of a fabric resulting from transverse displacements of fibres is called shear slip. It makes the fabric locally tighter and looser. Shear slip is an unwanted effect which is hard to control during the process. It primarily occurs during slipping of a fabric over a sharp edge or a rough surface. In the geometrical simulation program the shear slip has been ignored. The finite element simulation program is capable of taking the shear slip into account. It is however not implemented yet.
1.4 Deformation due to the trellis effect (Fig 1d)

The deformations of a fabric due to the trellis effect can be compared with pure shear strain of metals. During this deformation the fibres are not stretched: they only change of direction. Trellis deformations need relatively small forces and they can yield large displacements.

The trellis effect is limited by the maximum "deformation angle" which is about 30° for most fabrics. When this maximum angle is reached, further deformation of the fabric causes local buckling of the fibres. It is noted that a deformation angle of 30° corresponds with 30% strain in the 45 directions of the fabric.

In the geometrical simulation program the deformation of fabrics is based on the trellis effect only. It contains the maximum deformation angle as a limiting property of a fabric. In the finite element simulation the trellis deformation plays a dominant role as well. As remarked before it includes also the (much smaller) deformations due to the fibre stretching.

2 THE DEFORMATIONS OF A CURVED FABRIC.

With deformations resulting from the trellis effect only, the simulation of the deep drawing process of fabrics can be reduced to a purely geometrical problem. An important feature of the simulation is that the essentially "out-of-plane" displacements of the points of a draped fabric are constructed from locally "in-plane" displacements resulting from the trellis effect.

The geometric simulation starts with the choice of a point of contact between an initially flat fabric and a (doubly) curved surface which represents the desired shape of the final product. The points of the fabric in the direct vicinity of the contact point are moved to the surface within the restrictions of the trellis model for the displacements. This results in known local deformations of the fabric. By successively moving all the points of the fabric to the surface the deformations of the fabric as a whole can be calculated.

If the surface of the product is rotationally symmetric the whole deformation pattern of the fabric can be simulated by considering one quarter of the surface only. The simulation programs cover a great variety of surfaces with no symmetry at all and it is obvious that in these cases the whole surface must be considered.
3 THE PRINCIPLE OF THE GEOMETRIC SIMULATION

The principle of the geometric simulation can be shown very well by discussing the distinct steps in the computer program. They are:
- the generation of a database of the desired shape of the product for direct input in the simulation program.
- the calculation of the position of the points of a draped fabric on the surface of a product.
- the presentation of the generated data.

3.1 The input-data.

The surface of a product is numerically modeled with a surface modeller, for instance AutoCad. The generated model data are converted into a database which is suited for direct input in the simulation program. Then the orientation of the fabric is fixed relative to the product model. The maximum deformation angle and the meshwidth of the fabric are the last input data. (It is noted that the meshwidth is the most important parameter for the computing time.)

3.2 The calculation of the position of the points of a draped fabric.

The calculation starts at the highest point of the numerically modeled surface. This point is used as a reference point. The flat fabric is positioned in such a way that an intersection of two fibres coincides with the reference point. In the next step of the calculation two adjacent intersections, in the warp and weft direction respectively, are moved down to the surface. During this step the original, fixed directions of the fabric are maintained. The fourth intersection of the first quadrangle is then calculated within the restrictions of the trellis deformation model for the fabric. After the first quadrangle has been completed extensions are made:
1. Select the highest intersection on the edge of the part of the fabric which has already been draped.
2. At this intersection extensions are made in such a way that the deformation of the fabric is minimal. For that purpose a simple test with regard to the summed deformation angles of the fabric as it is draped so far is included in the program. If the results of the test are not satisfactory the last step or steps of the simulation must be corrected. The test does not exclude a possible occurrence of a local deformation angle greater than the maximum deformation angle of the fabric. If such an angle occurs the simulation stops and must be restarted at a previous stage.

It is obvious that a shape can be draped in many ways. The built in tests, however, result in simulations which are in good agreement with experimental results.
3.3 The output data.

The output of the geometrical simulation program can be shown in two ways:
- a view of the deep drawn product from an arbitrary direction (fig2). The deformed quadrangles can be given a colour, making the identification of areas of large deformations easier. The information can be used to localize the probable problem areas with respect to folds.

fig 2 An object shown from different directions

- the shape of the fabric in unfolded situation (fig 3). This information can be used for the cutting of the fabric.

fig 3 The unfolded situation of the object of fig 2
4 THE PRINCIPLE OF THE FINITE ELEMENT SIMULATION.

The name finite element simulation originates from the fact that the fibres are modelled as one dimensional beams, this is analogous to other finite element programs. The principle of this simulation can also be shown by discussing the steps in the computer program. They are:
- The definition of the fabric, the mould and the blankholder in the finite element program.
- The calculation of the position of the points of a draped fabric on the surface of a product.
- The presentation of the generated data.

4.1 The definition of the fabric, mould and blankholder.

The fabric is defined as a collection of beams which have no bending stiffness or torsional stiffness (one dimensional element). The fabric is fixed by springs at the edges of the fabric (fig 4). The initial orientation of the fabric can be obtained from the geometrical simulation of the same mould. At the nodes of the fabric forces and/or displacements can be prescribed in the X, Y and Z direction.

![Figure 4: The model of the fabric used in the finite element simulation](image)

The mould and blankholder can be defined in the same way as in the geometrical simulation. For the present study a hemisphere was chosen.

The blankholder in that case is a simple plate with a circular hole in the middle.
4.2 The calculation of the position of the points of the draped fabric.

The calculation starts with moving the mould towards the blankholder in which the fabric is clamped until it touches the fabric. After this first step the remainder is calculated according to the next flowchart:
1 Determine the smallest value $dz$ of the distances between the still free intersections and the mould and move the mould over a distance $dz$ perpendicular to the fabric.
2 Calculate the position of the intersections of the fabric. This is done by considering the force equilibrium in three directions in every intersection.
3 Determine which points should be fixed ("frozen"). These are the points which are in contact with the mould. (It is noted that in real deep drawing the heated fabric reinforced thermoplastic cools down quite fast as soon as it touches the cold mould.)
4 Check whether the desired depth is reached. As soon as this occurs the process is stopped.

4.3 The output-data

The output of the finite element simulation program can be shown in the same way as the output of the geometrical simulation program. In this way possible problems areas can be determined.

Stretching of the fibres is included in the finite element simulation since it gives us information about tension and compression zones. Compression zones should be avoided because of possible buckling of the fibres, and related wrinkles.

5. RESULTS OF THE GEOMETRICAL SIMULATION

A T-shaped object (fig 5) was chosen for the geometrical simulation because it shows the possibilities of the simulation very well.

fig 5 The T-shaped product
fig 6a  T-shaped object covered with 45° fabric
Section A is fixed before the simulation

fig 6b  T-shaped object covered with 45° fabric
Section B is fixed before the simulation
Figures 6 and 7 show the influence of the original position of the fabric on the simulated pattern very well. In figure 6 the position was chosen 45° relative to a principal axis of the product. In figure 6a section A was fixed, leading to areas of high deformation in section B. In figure 6b section B was fixed, leading to areas of high deformation in section A. Figure 6a shows the best draping since the deformations are smaller than in figure 6b. In figure 7 the orientation was 0° relative to the principal axis of the product. This orientation yields less deformation than the 45° orientation in figure 6. Comparing figures 6 and 7 it is obvious that the T-shaped object should be draped with the 0° orientation. A real product, based on the simulation of figure 7, is shown in figure 8.
fig 9a The original non drapeable shape

fig 9b The redesigned part

If an object cannot be draped properly whatever the original orientation of the fabric is, an option is to change the geometry, or what is equivalent, to redesign the part. An example of such an object is shown in figure 9. Figure 9a represents the original shape, figure 9b shows the part as it was redesigned with the help of the draping simulation.

6 RESULTS OF THE FINITE ELEMENT SIMULATION

The finite element simulation is still in an early stage of development. This is the reason why a simple half sphere is chosen for the mould. An important reason for the development is the capability of the program to simulate forces on the fabric or prescribed displacements. With the geometrical simulation this is impossible. In the real process forces and prescribed displacements may be used (and sometimes need to be used) for guiding the fabric in order to prevent folds or wrinkles.
Figure 10a shows a fabric with the springs on its edges before deep drawing. Figure 10b shows the fabric after the deep drawing. No prescribed displacements were used, so the fabric was free to move. The springs show large deformations, whereas the fibres are hardly stretched.

Place where the 'pins' are put during simulation (4x)

Figure 11a shows the flat fabric and Figure 11b shows the deformed fabric.
Figure 11a shows the fabric with springs on its edges before deep drawing, this time pins are simulated in the four corners (Hence no displacements are allowed for these intersections). Figure 11b shows the fabric after the deep drawing. Compared with figure 10b the elongations of the springs are smaller in the neighbourhood of the four corners, this will lead to tension in the fibres in these areas. By using pins (or forces) tension zones can be created in the fabric during deep drawing and compression zones can often be avoided.

7 EXPERIMENTAL RESULTS

Computer simulations provide fabric patterns which match the shape of a model and they yield information about the necessary guiding of the fabric. Standard deep drawing techniques without guiding will not result in products with the predicted pattern. For instance the deformed areas of the product of figure 12, are difficult if not impossible to obtain without special guiding of the fabric. If guiding is not used folding and tearing of the fabric can occur.

![The dog bone shaped product and its simulation](image)

fig 12 The dog bone shaped product and its simulation
So in order to avoid wrinkles it is necessary to guide the fabric during deep drawing. It is then possible to obtain products of good quality with fibre orientations similar to the computer pattern. The edges of the fabric are the most suitable areas to realize the guiding. The guiding forces can be uniformly distributed, or applied at discrete points. Furthermore it is important that they are applied in such a way that the pattern of the fabric at the edges around the product fits with the described pattern on the product itself.

The guiding of the product shown in figure 12 can be done by using pins in the edges of the fabric. These pins should be placed at the points shown in figure 12, for different products different places of the pins are needed. The pins will cause tension in the fabric at certain places, it helps the fabric deforming itself using the trellis effect. After the deep drawing the edges of the product will be torn. This, however, is no problem since the edges are cut off in general.

Figure 13 shows the tooling needed for the deep drawing of the dog bone shaped product. The applied sheet material in this case is a laminate containing several equally orientated, impregnated fabrics. Extra layers of pure resin can be incorporated in the laminate. They facilitate interlaminar slipping and yield the required fibre volume content. Experiments show no essential differences between deep drawing of laminates and of a single, impregnated fabric.
8 CONCLUSIONS

From a comparison between computer simulations and the experimental results, it may be concluded that the patterns of the applied fabrics are in good agreement. Although only a few types of products were considered in the present paper we think that the following, more general conclusions are justified:

1. Simulation can be used to decide whether a product can be deep drawn or not.
2. Simulations yield practical information for the deep drawing process.
3. Products made in agreement with computer simulations are of good quality in terms of sharp corners and absence of wrinkles.