SIMULATING AND VALIDATING THE DRAPING OF WOVEN FIBER REINFORCED POLYMER

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ABSTRACT

This study presents forming simulations on woven textile composites using (a) an explicit finite element method and (b) a kinematic mapping scheme. Both methods are compared with experimental results that are obtained by determining the fiber orientations of thermoformed glass/PP woven composites using a 3D image correlation method. The kinematic draping solution is also compared with the experimentally measured thickness of the formed ply. The goal of this study is to investigate whether the complex behaviour of woven textile composites can be approached by a kinematic mapping algorithm. It was found that the mapping approach severely fails in predicting the fiber reorientation and thickness distribution that occurs during forming due to unrealistic initial conditions and a simplified material model. The FEM simulation gives a reasonably good prediction of the fiber reorientation and seems the most promising technique in having good draping simulations.

1. INTRODUCTION

The manufacturing of curved woven reinforced composites requires a forming stage in which the preform takes the desired shape. A typical characteristic for woven fabrics is the high resistance to deformation in the fiber directions. This results in a material that deforms primarily by in-plane shear. In-plane shearing makes fabrics very efficient when curved shapes need to be formed, but results in fiber reorientation in order to adapt to the mould. The fiber directions affect the mechanical performance of the final formed composite. Therefore, an important effort is currently made in order to predict the forming of textile composites [1]. The main objective is to create a tool to support process optimization and reduce the cost for designing a composite product. Two major modeling approaches are commonly used in composite sheet forming [2]. The earliest and easiest techniques, dated from 1950s [3], are based on mapping approaches e.g. kinematic models. No constitutive behaviour needs to be known since no forces are calculated. In contrast to these mapping schemes, the constitutive behaviour is required for mechanical approaches.

In order to validate whether simulation tools accurately predict the local properties, experimental data is needed. Research has been done to obtain fabric deformation data [4, 5]. At the University of Nottingham a method has been developed based on measuring the deformation of a square grid printed onto the fabric. The deformation of the surface is measured by capturing two digital images of the grid from different orientations. This paper uses a similar experimental technique to measure the local shear profile.

2. MATERIAL AND METHOD

2.1 Material

The material used in this research is a glass fiber reinforced polypropylene fabric; known under the trade name Twintex®. Table 1 summarizes the properties of the weave. Note that it is a highly unbalanced twill weave, with a very high crimp of the warp.

Table 1. Twintex® TPEET44 (warp/weft)

Areal density [g/m²]	1485
Linear density of the yarns [tex]	1870 /2 * 1870
Ends/picks count [1/cm]	4.1 / 1.9
Crimp [%]	10.3 / 0.1

2.2 Draping

The preconsolidated material was deformed using a non-isothermal stamping process. After heating the material till a temperature above the melting point of the matrix, it is formed and pressed in a rigid “half-salami” shaped mould. Three preform orientations, specified as the angle between warp yarns and the long symmetry axis, have been investigated: 0, 30 and 45°.

2.3 Shear angle measurement

Initially the warp and weft yarns are perpendicular to each other. Though, since the key deformation mechanism in fabric draping is in-plane shear, the enclosed angle between the two fiber directions will change. When comparing predicted with experimental data, the complement of this angle, called the shear angle, is taken as indication for the local fiber reorientation.

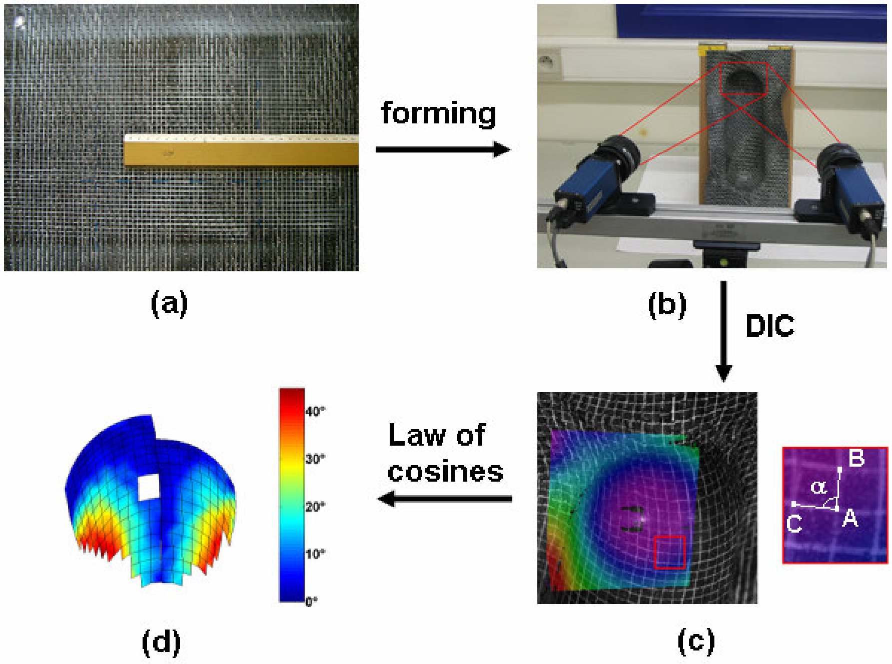


Figure 1: Overview of the method used to determine the shear profile of a formed composite.

Figure 1 illustrates the subsequent steps needed to obtain a local shear profile of the formed composite. In order to measure the amount of shearing, it is necessary to track fiber positions and orientations within the deformed fabric. Therefore, a reference pattern, indicated in figure 1 (a), follows the yarns during shearing. In a latter stadium, it also serves as pattern needed for Digital Image Correlation (DIC). This pattern is sprayed with white paint onto the black preconsolidated sheets with the help of a stencil that has parallel grooves. The pattern consists of a grid, with a grid size of 5 by 5 mm² and a line thickness of about 1 mm. After forming, the surface of the composite is measured by using a 3D DIC technique. Figure 1 (b) depicts this technique that uses a camera system (Limess). First stereo-correlation and calibration of the camera set-up is performed from which the relative camera position and lens distortions are identified. Afterwards, both cameras capture an image of the same region. These two images are combined to obtain the three-dimensional coordinates of the surface, shown in figure 1 (c). The coordinates of the grid intersection points are extracted and the angles between the grid lines are calculated using the planimetric law of cosines. A shear angle at the point A is calculated as average of four angles, complimentary to the four angles α for the grid lines joining at A. Figure 1 (d) presents a measured shear angle distribution of a deformed sheet for a 0° ply-orientation, the 'hole' in the middle of the shape is due to reflection effects in step c.

The main benefit of this technique lies in the fact that the surface is measured via a contactless method. A drawback lies in the difficulty of tracking the fiber direction. When applying the reference pattern on the pre-consolidated sheets, it is assumed that the gridlines are parallel with the fiber directions. In practice it has been observed that the fibers inside the sheet are not straight, making it impossible to track them perfectly.

2.4 Thickness measurement

The thickness of the thermoformed sheets is determined for the 0° orientation. In each hemisphere 4 points are determined using a dial indicator, with a small rigid point taken as reference. Since it is difficult to measure perfectly perpendicular to the surface, the minimum value obtained was taken as the thickness. Figure 2 indicates the different locations of the measurements. Note that point A and B are taken in zones with low shear angle, whilst at the points C and D the highest shear angles are located for the 0° fabric orientation.

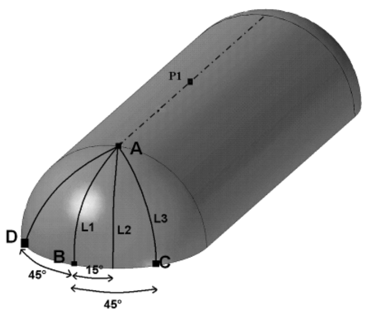


Figure 2: Male mould

3. SIMULATION

2.1 Kinematic draping

A commercial program that uses the kinematic approach to simulate the draping of woven clothes is Quikform. It allows draping the surface using an advancing front approach (AFA) from the date of an initial impact point between the fabric and the surface and the initial fibre directions at this point. The distance between two crossover points is calculated along geodesic lines of the surface [6].

Boundary conditions are needed to provide for a unique draping solution. They control the initiation and direction of draping and consist of (a) an initial contact point and (b) warp/weft directions in this point. The contact point of draping needs to coincide with a node on the meshed mould surface. The initial warp and weft directions are specified by defining a draping vector in the contact point. For the simulations described in this study, the initial contact point was chosen to be the symmetry point of the mould, i.e. point P1 in figure 2.

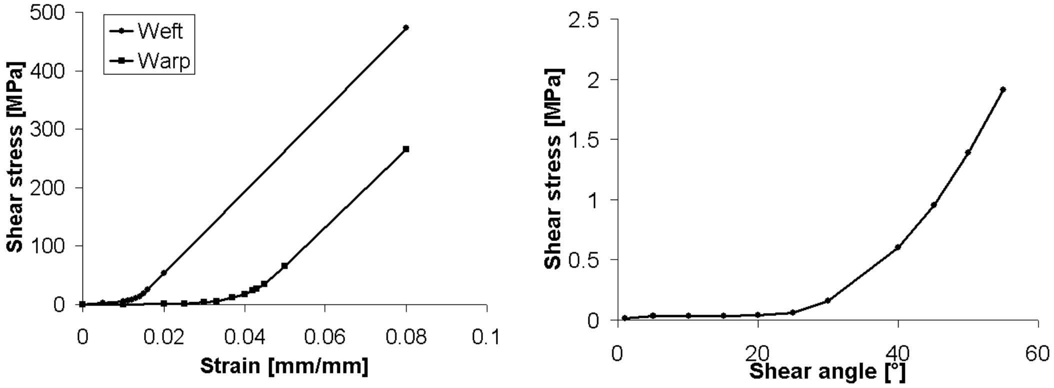
The thickness of the fabric after draping is calculated by assuming a conservation of mass, which results in the following formula:

$$t = \frac{t_0}{\cos(\theta)} \qquad (1)$$

where t is the thickness after forming, t_0 is the thickness of the undeformed ply and θ is the shear angle.

2.2 FEM simulation

FEM-simulations are performed by using commercially available software that uses an explicit approach to solve the resulting equations, namely PamForm. The material model in PamForm uses a "biphase" model with thermo-visco-elastic matrix and elastic fibers. The fibers are assumed to be embedded in the elements and move with the element in intra-ply shear deformation. The shear modulus characterization is typically done by performing picture frame or bias extension tests [7]. The elastic properties of the fiber sheet are based on the tensile properties of the fabric in warp and weft direction, measured via uniaxial tensile tests. Figures 3 (a) and (b) present the measured shear and uniaxial tensile data.



(a) **(b)**

Figure 3: Mechanical behaviour of the fabric for (a) uniaxial tension and (b) in-plane shear

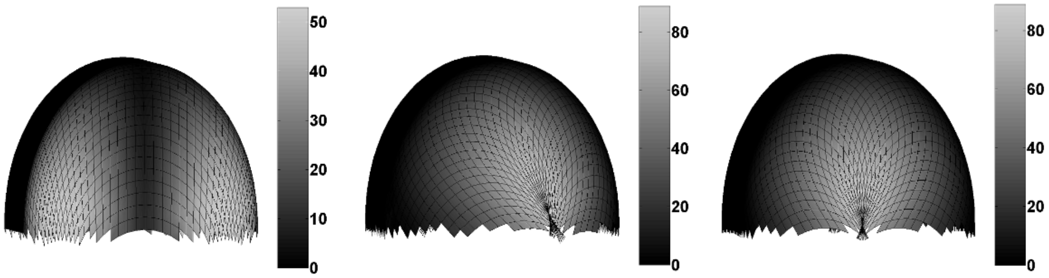
These curves are used as the material properties of the blank for the forming simulation. The non-linear behaviour of the material is a consequence of the woven structure of the fabric. The increase in stiffness of the in-plane shear behaviour is due to compaction of the yarns when the shear angle increases. When the yarns are compacted, deformation becomes more difficult, which will eventually lead to wrinkling when the "locking" angle is reached. The low stiffness at the beginning of the tensile curve is due to the undulation of the yarns in the tensile direction. This de-crimping causes the yarns to straighten and thus deformation becomes more difficult. An explanation for the different behaviour in warp and weft direction lies in the unbalanced nature of the fabric. Weft of this fabric is not crimped (crimp is 0.1%), on the contrary, the warp is heavily crimped (crimp is 10.3%) and thus more undulation occurs. During the simulations performed in this study the effects of heat transfer and matrix viscosity are neglected.

Owing to symmetry, for a 0° perform orientation only a one-quarter is analysed. For 30 and 45° the whole blank needs to be considered since the fabric is unbalanced. The contact that occurs between the different object during forming is defined as coulomb friction with a friction coefficient of 0.3. Though, while evaluating some preliminary simulations it was noticed that the preform and punch didn't remain in contact during forming. The detachment of the preform has no physical meaning; therefore the contact definition was extended by defining a separation stress. This option allows to model sticking contact, i.e. when a blank node touches at the punch surface, there is no more relative displacement along the normal direction.

4. VALIDATION

4.1 Shear angle profile

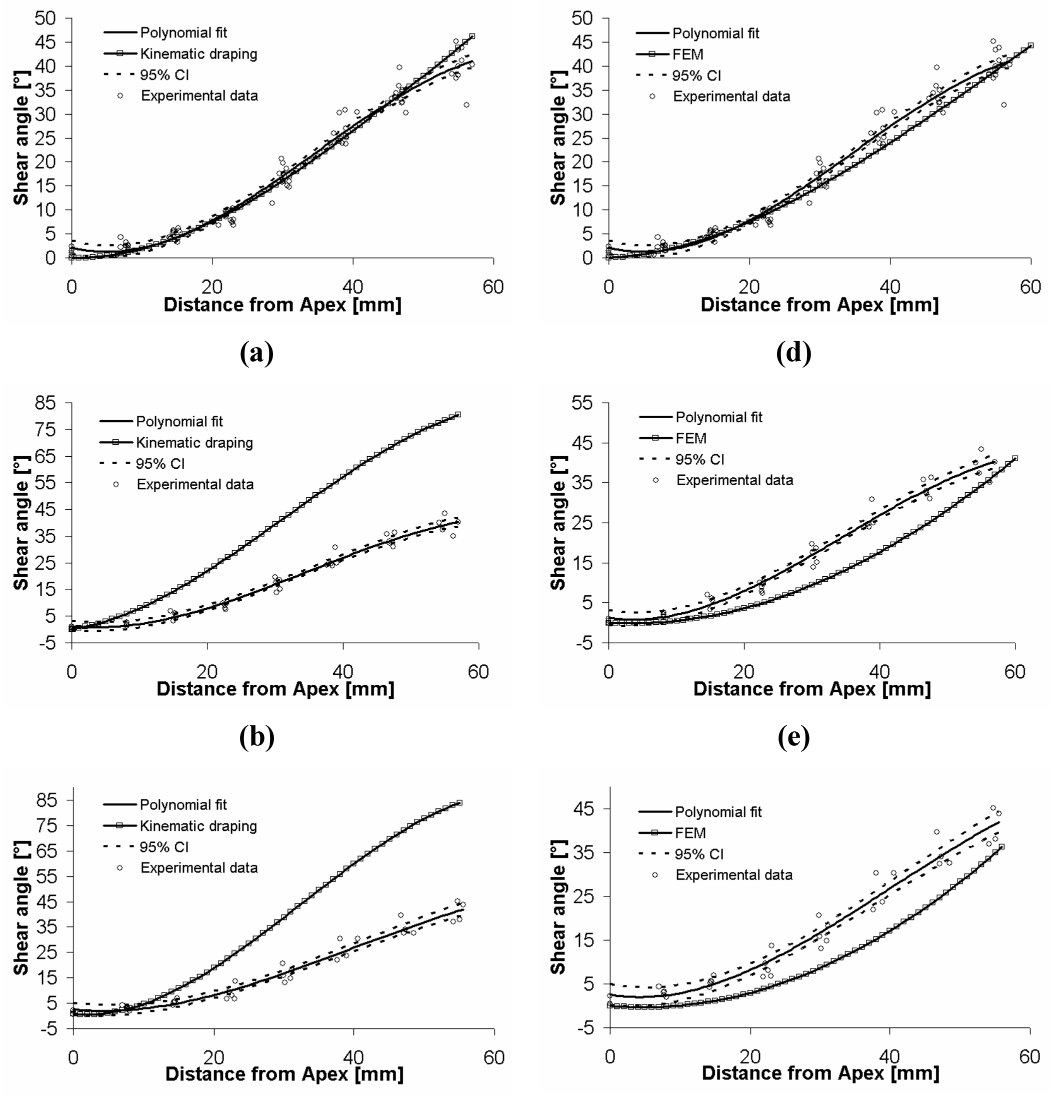
From figure 4 it can be concluded that the shear angle level and distribution are highly depended on the boundary conditions. The fibers reorient drastically in case of a 30 and 45° orientation.



(a) **(b)** **(c)**

Figure 4: Kinematic draping solution for the shear angle profile with contact point P1 and viewpoint VP1 for (a) 0° ply-orientation, (b) 30° ply-orientation and (c) 45° ply-orientation

To compare the experimentally obtained shear data with the kinematically predicted one, cross sections where most shearing occurs are examined. Figure 2 gives an overview of the different cross sections for different ply-orientations. The line L3 corresponds with the examined cross section for a 0° preform orientation, line L1 is chosen to compare the data for a 45° preform orientation. For a 30° ply-orientation the cross section, indicated by L2, forms an angle of 15° with the long symmetry axis of the mould. A third order polynomial is fitted through the experimental data and the 95% confidence intervals are determined.



(a) (d)

(b) (e)

(c) (f)

Figure 5: Comparison between kinematic draping and experimental results for (a) 0° ply-orientation, (b) 30° ply-orientation and (c) 45° ply-orientation and between FEM simulation and experimental results for (d) 0° ply-orientation, (e) 30° ply-orientation and (f) 45° ply-orientation

From figure 5 (a) it can be concluded that for the 0° orientation the agreement between the experimental and the kinematic draping results is good. At higher shear-angles there seems to be a small discrepancy between the model and practice. The experimental shear angle is smaller than the predicted angle. The shear angle starts levelling off due to fibre locking; the region were the locking starts to increase lies at about 30 to 40°, visible in figure 3 (b). The draping model assumes a negligible shear resistance and therefore cannot account for increasing shear resistance above the locking angle. For drape orientations other than 0°, the results from the kinematic model do not agree at all with the experimental results. The oversimplification of the fabric deformation in this model gives shear angles up to 88° in case of the 30° preform orientation, which is impossible. Figures 5 (b) and (c) visualise the large difference between the kinematic model and the measured shear angles for a 30 and 45° orientation.

For the FEM simulations experimentally obtained shear data were also compared with the predictions. Again the cross sections, shown in figure 4, are analyzed in order to validate the forming simulation. From figures 2 (d), (e) and (f) it can be concluded that for all ply-orientations the agreement between the experimental and the simulated draping results is reasonably good.

The deviations between experiments and predictions can be explained by material data input and by the “oversimplified material model” that does not yet consider the complex interaction between warp and weft yarns of the fabric. The non-linear zone in figure 5 (b) depends on the strain-ratio between warp and weft [8], though in this material model this is not taken into account. Different research centers have carried out a benchmark on the shear behaviour of woven textile composites [9] and [10]. It was shown that the picture frame test is not yet completely controlled, resulting in erroneous material data input. A third possible cause for the deviations is the complex contact behaviour between the preform and the mould. The contact definition in PamForm does not take into account the dependency of the friction on the process parameters [11].

From above discussed results, it can be concluded that the kinematical draping method is not appropriate for accurately predicting the fiber directions of a fabric sheet after forming. The origin for this erroneous behaviour lies in the AFA used by the draping algorithm, which has 1 initial contact point. In reality draping initiates from a line of first contact formed by the long symmetry axis of the half cylinder. Using the AFA, the sequence in which the intersection points of the fabric are calculated is not correct. This affects the draping simulation, since the coordinates of one crossover point are calculated from two neighbouring points and the surface of the mould.

It can also be stated that FEM-simulation seems to give reasonably good results for predicting the fiber re-orientation during forming. Though, the constitutive model is still too simplified to exactly describe the forming behaviour of woven reinforcements.

4.2 Thickness

Table 2 indicates the average values of the thickness determined at the different location indicated in figure 2. These average values are taken from 6 measured shapes of 0° fabric orientation; for each shape the two hemispheres are processed together, making use of the symmetrical loading case. The original thickness of the preconsolidated sheets is 1 mm.

Table 2. Comparison of thickness between kinematic draping and experimental results

Point location	Measured thickness [mm]	Thickness (Kinematic draping) [mm]
A	0.86 ±0.05	1
B	0.82 ±0.07	1
C	1.20± 0.11	1.5
D	1.16±0.13	1.5

The reduction in thickness at the apex of the mould (point A) is due to a localized high pressure in this point as the male and female mould first contact at the line which connects the two apexes of each half-hemisphere. The high pressure causes the matrix material to flow away from this region [12].

The reduction in thickness at location B is not so obvious. At this point a lower pressure will occur then initially at the apex, thus one expects to see an increase in thickness in relation to point A. A possible explanation could be that due to the high crimp height, the fabric has difficulties to slip over the rounding of the female mould. The material is further drawn in, but the transverse yarns are restricted to move, consequently the tensile state is increased, which leads to a decrease in thickness. It is clear from table 2 that the thickness increases with increasing shear angle (points C and D). This phenomenon occurs since the fibers are compressed laterally when they are sheared. Because of this thickness variation, the applied pressure during consolidation will not be distributed homogeneously over the fabric. Since the void content is dependent on pressure [13], this will result in locally different consolidation grades. The kinematic draping model combined with a conservation of mass predicts an increase in thickness with increasing shear angle. Though, since the real flow behaviour that occurs when the material is pressed between the punch and the die is not considered, the predicted values are an overestimation.

6. CONCLUSIONS

This study presents a comparison between two different modelling approaches commonly used in the simulation of draping woven composite fabric. A first being a mapping approach, which only considers in-plane shear as deformation mechanism. A second more realistic approach is a mechanical model, which considers the non-linear elastic behaviour of the fabric and the boundary conditions during forming. Both modelling approaches are compared with experiments.

Thickness measurements have been performed using a dial indicator. Due to a heterogeneous pressure distribution a decrease in thickness is observed at the point where the mould and the fabric first come in contact. The thickness at the edges decreased where the fabric gets stuck due to the mould geometry and the high crimp heights of the fabric, while the thickness increases when the shear angles increase. Solely using the kinematic constraints of the mapping approach, results in an overestimation of the thickness.

From the comparison with the measured shear profile, it can be concluded that the mapping approach severely fails in predicting the fiber reorientation that occurs during forming. The main sources of these faulty predictions are (a) the strategy of the mapping simulation and (b) neglecting the real draping behaviour of a woven fabric. On the contrary, a more refined mechanical simulation approach gives a reasonably good prediction of the fiber reorientation. The deviations noticed between experiments and predictions can be explained by material data input and by the “oversimplified material model”. Also contact between preform and the mould is a factor that cannot be neglected and certainly needs to be examined further.

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