On the formability of multi-layered fabric composites

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SUMMARY

Composite laminates consisting out of fabric plies with different fiber orientations are deformed by using a hemispherical shaped punch. A drastic decrease in formability is noticed when the relative orientation between two neighbouring fabrics increases. This phenomenon is triggered by the increasing difference in local deformation and the high friction coefficient between neighbouring plies.

Keywords: forming, textile, wrinkling

INTRODUCTION

Forming of woven reinforced polymers is often accompanied by unwanted shape distortions. The most common is wrinkling. Wrinkling occurs when the in-plane compressive stresses in the laminate exceed a critical value [1] or when the shear locking angle is reached [2].

Formability studies of fabric reinforced thermoplastic polymers are usually confined to relatively easy drapable laminate configurations, like single layers or laminates where the relative orientation between the plies is small [3-5]. The reason being the lack of large shape distortions when the relative orientation between neighbouring fabric plies is small, making them easier to form. Ten Thije [6] noticed that a quasi-isotropic lay-up of woven fabrics causes severe wrinkling during forming. He attributed this phenomenon to the restriction of the interply slip by the stiff fibers in the neighbouring plies. Loads are transferred between the individual plies by interface tractions and wrinkling occurs, but no solution to reduce the occurrence of these wrinkles was proposed. Friedrich et al. [7] showed that slip of the individual plies across one another is critical to accommodate to complex mould geometries. When interply slip is not allowed, fiber buckling and wrinkling will occur, resulting in poor mechanical and aesthetical properties. De Luca et al. [8] implemented a viscous-frictional contact behaviour in a FEM code, by modelling each ply of the laminate separately with shell elements and using appropriate viscous-friction laws between shells to account for resin dominated interply shearing. They reported that quasi-isotropic fabric laminates cause more wrinkling than cross-ply fabric laminates. [9].

The goal of this study was to investigate the influence of the fabric layup on the formability. Therefore, fabric reinforced thermoplastic laminates with different fiber orientations are formed by using a hemispherical shaped punch. Afterwards the local shear of each ply is determined and the maximum shear that occurs is taken as a characteristic for the formability of the fabric laminate.

MATERIAL

The material used in this research is a glass fiber reinforced polypropylene fabric; known under the trade name Tepex®. Figure 1 depicts the unit cell of the fabric. It is a 2x2 twill weave with an areal density of 290 g/m².

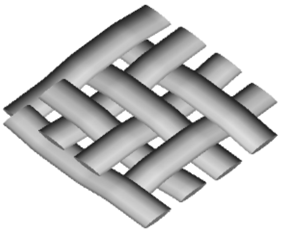


Figure 1. Unit cell for TEPEX

METHODS

Preconsolidation

Prior to forming, a two-layered stacking of the fabric is preconsolidated using a hot press. The layers in this laminate have a relative orientation, defined by the angle between the warp directions of the fabric plies, of 0, 15, 30 and 45°. To show the influence of the friction on the formability, an extra PP-film of 0.5 mm is pressed between the layers of a laminate with a 45° relative orientation difference. Finally the stacking is preconsolidated with a pressure of 0.5 bar at temperature of 180°C.

Forming

The preconsolidated laminate is deformed using a non-isothermal deepdrawing process. After heating the material to the desired temperature, it is formed using a rigid hemispherical shaped male mould with a diameter of 95.1 mm. Figure 2 a scheme of the forming stage. The die consists of an open ring with a diameter of 100 mm and is rounded at the edge to a radius of 12.5 mm. A mould heating machine heats the male punch to 85°C, the die is not heated.

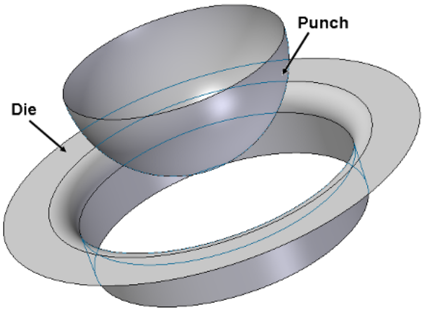


Figure 2. Set-up of the forming stage

Shear angle measurement

After forming the local amount of shear is measured using the method explained in [10]. Figure 3 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. A reference pattern, indicated in Figure 3(a), is sprayed with white paint onto the black preconsolidated sheets with the help of a stencil that has parallel grooves. This reference pattern follows the yarns during shearing. In a latter stage, it also serves as pattern needed for DIC. After forming, the surface of the composite is measured by using a 3D DIC technique. Figure 3(b) depicts the setup that uses a camera system, which consists of two cameras that both capture an image of the same region. In Figure 3(c), these two images are combined to obtain the three-dimensional coordinates of the surface by using the software of correlated solutions, namely VIC 3D [11]. The coordinates of the grid intersection points ABC are extracted and the angles between the grid lines are calculated using the 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 3(d) presents a measured shear angle distribution of a deformed single layered laminate. The gap in this figure is due to light reflection zones where the DIC algorithm fails.

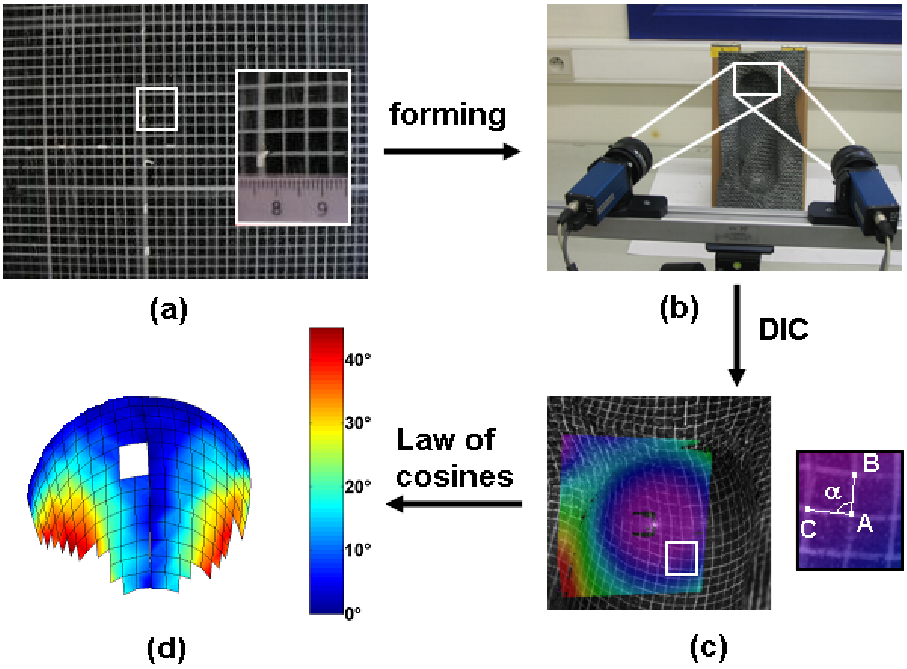
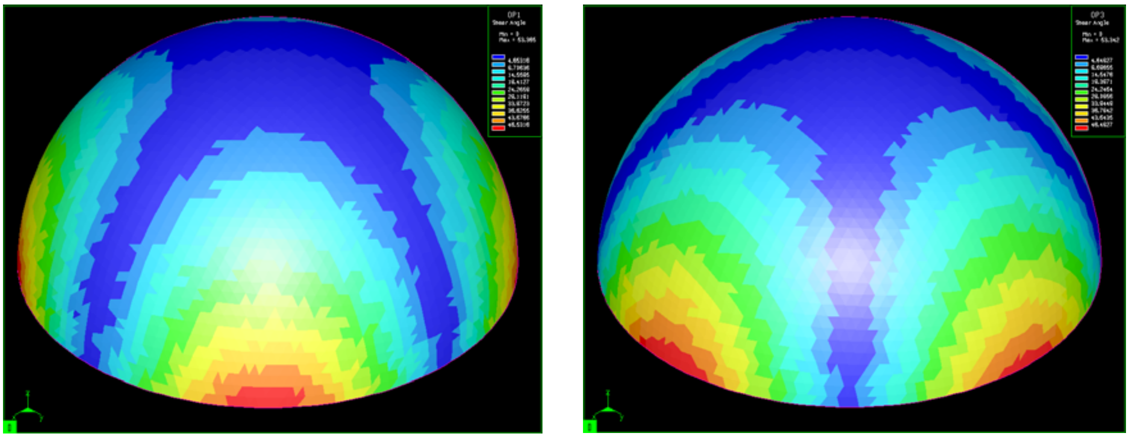


Figure 3. Subsequent steps to measure the shear profile of a formed composite [10].

Kinematic draping

The kinematic draping model is based on the assumption that the deformation is restricted to in-plane shear. A commercial program that uses the kinematic approach to simulate the draping of woven clothes is Pam-QuikForm. The mould surface is meshed using triangular and quadrilateral shells and the distance between two crossover points is calculated along geodesic lines of the surface [12]. It allows draping the surface using an advancing front approach, starting from the data on an initial contact point between the fabric and the surface of the mould and the initial fibre directions at this point. These initial boundary conditions are needed to provide a unique draping solution. The contact point of draping must 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. This method is confined for draping of single layered fabrics, since it can not take into account the interply slip that occurs when multiple layered materials are formed.

In this study the kinematic draping solution of a single layer is used to investigate the difference in local deformation inside multi-layered laminates. First a single layer of the fabric is draped on the male punch using the apex as the initial contact point. Different initial fiber direction are defined, the fabric is rotated 15, 30 and 45°, corresponding to the different orientations used in the experimental forming. From the kinematic draping solution, the amount of displacement each crossover point undergoes is obtained. The difference in local displacement between two layers is then calculated for a 0, 15, 30 and 45° relative orientation. Figure 4 shows the kinematic draping solutions for a 0 and 45° initial fiber direction.



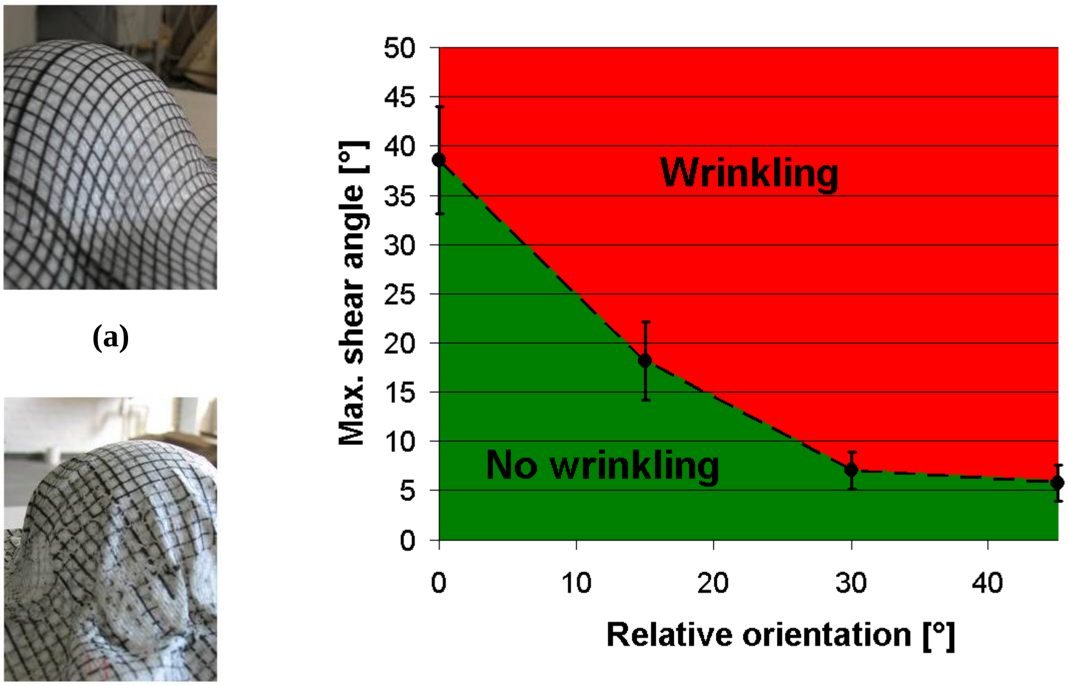
(a) **(b)**

Figure 4. Kinematic draping solution for (a) 0° and (b) 45° initial fiber direction.

RESULTS

Forming

Figure 5(a) shows a deepdrawed laminate for a 0° relative orientation, no wrinkling occurs. Increasing the relative orientation gives rise to more wrinkling. This can be seen in Figure 5(b) that shows heavy wrinkling in the formed hemispherical laminate with a 45° relative orientation of the plies.



(a)

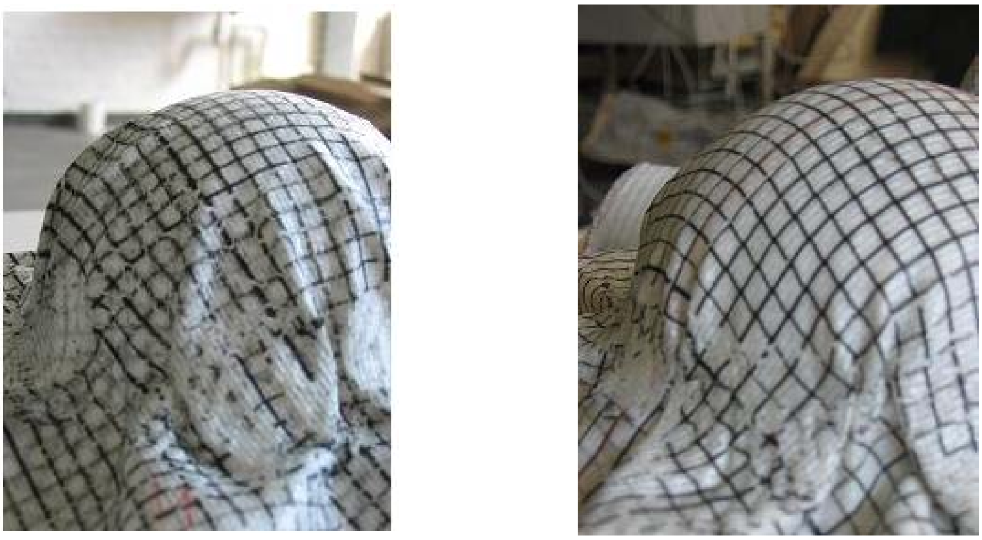
(b)

(c)

Figure 5. Deepdrawed laminate with (a) a 0° relative orientation and (b) a 45° relative orientation, (c) Forming Limit Diagram.

The maximum amount of local shear is determined by taking the maximum value obtained from the shear angle measurement. The shear is only calculated for areas where no wrinkling is found. The highest shear angles are found close to the starting point of a wrinkle. It seems intraply shear is prevented, consequently the flat fabric laminate will adapt to the mould by wrinkling. Figure 5(c) visualizes the maximum shear angle measured on a formed hemisphere for different relative orientations. It is noticed that the measured maximum shear angle rapidly decreases as the orientation between the neighbouring plies increases. This figure can be interpreted as a forming limit diagram for a two-layered stacking. It shows the critical combination of shear, which forms a measure for the complexity of the mould, and difference in relative orientation in the laminate at the onset of wrinkling. The dotted line forms the forming limit, whenever this line is exceeded the amount of intraply shear needed to form the laminate is too high and thus wrinkling will occur. For example, if a laminate consisting of two layers of TEPEX®-material with a relative orientation of 30° needs to undergo more than 7° of shear to adapt to the mould, wrinkling will occur.

The influence of friction between the layers is assessed by increasing the interlayer thickness between the plies. Vanclooster et al [13] noticed that increasing the interlayer thickness severely lowers the friction coefficient between neighbouring plies. A polypropylene sheet of 0.5 mm is pressed between plies with a 45° difference in orientation during preconsolidation. From Figure 6(a) and (b) it can be concluded that the amount of wrinkling significantly decreases. This observation is confirmed by an increase of the maximum shear angle from 6.24° ± 2.37 to 22.51° ± 4.87°.



(a) **(b)**

Figure 6. Deepdrawed laminate for a 45° relative orientation (a) without extra PP in the interlayer and (b) with a PP-sheet of 0.5 mm in between the neighbouring plies

Kinematic draping

In order to better understand the origin of wrinkling in 2-layered fabric composites, the difference in local deformation between two neighbouring plies obtained by kinematic draping is investigated. The local displacement difference is normalized by dividing it by the radius of the punch (47.55 mm). First a kinematic draping profile for different fiber orientations is obtained, shown in Figure 4. Figure 7 compares the profile of the local difference in displacement with the formed laminate. In Figure 7 (a), it is seen that for a 0° relative orientation, no wrinkling occurs. For this relative orientation, the local deformation difference between the neighbouring plies is almost zero. This is due to the fact that the zones where the deformation, i.e. in-plane shear, occurs lie exactly on top of each other. The small values at the edge of the hemisphere are due to rounding errors in the calculations.

For a 15° relative orientation, in Figure 7(b), the difference in local displacement is much more pronounced and goes up to 0.09, which in case of a punch with a radius of 47.55 mm, means that the maximum difference in local displacement is 4.28 mm. This is the maximum amount of interply shear that needs to occur between the plies in order to adapt to the mould perfectly. Comparing the deepdrawed laminate with the local displacement profile, it is noticed that wrinkling happens at those places where intra- and interply shear need to take place. Since the high friction between the layers doesn’t allow the individual layers to move separately, loads are transferred between the individual plies by interface tractions. Figure 8 shows for a 45° relative orientation that, intraply shears invokes compressive forces in the stiff fiber directions of the neighbouring ply. These compressive stresses induce wrinkling of the laminate.

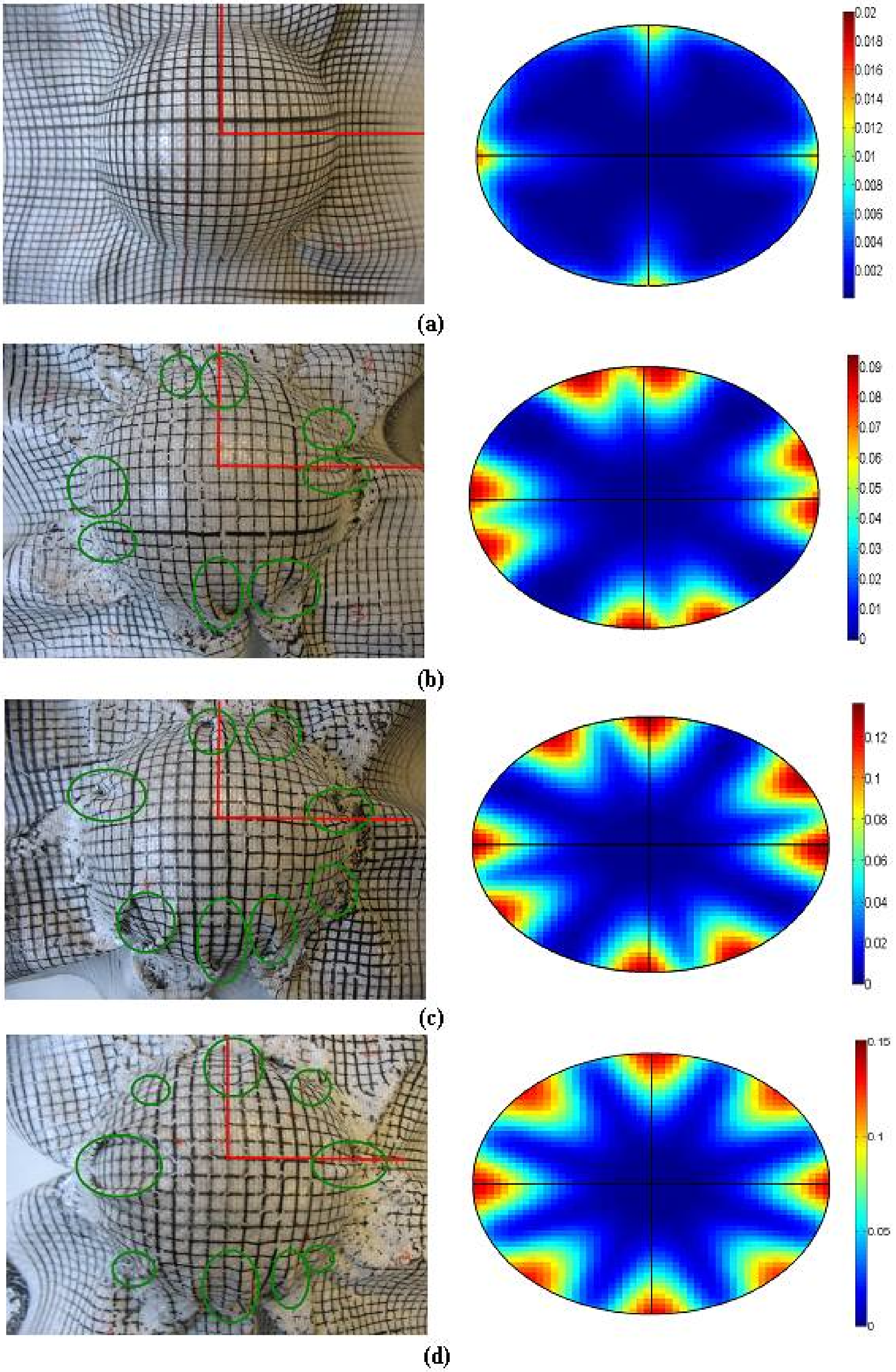


Figure 7. Comparison between the local difference in displacement and the formed laminate for (a) 0°, (b) 15°, (c) 30° and (d) 45° relative orientation.

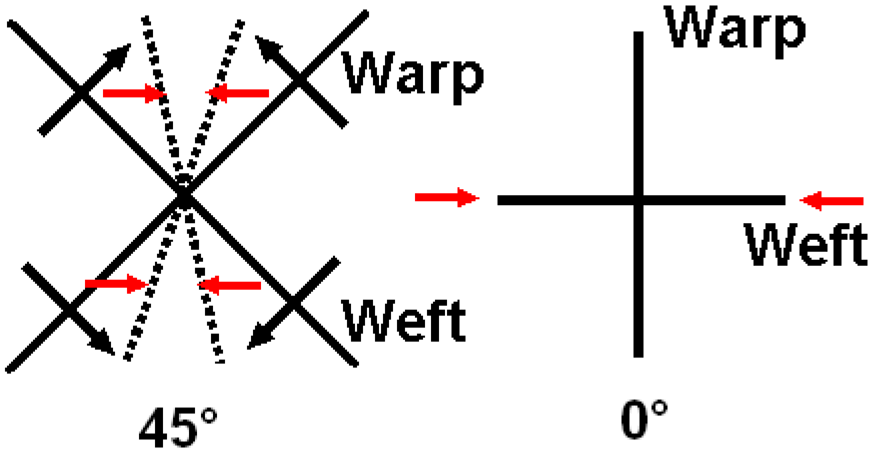


Figure 8. Compressive stresses arise inside a neighbouring ply

Increasing the relative orientation difference increases the difference in local displacement. From Figure 7(c) and (d) it can be seen that for a 30° difference in orientation the maximum value is 0.12 and for a 45° relative orientation it goes up to 0.15. This increase is noticed by more severe wrinkling. For these relative orientations the individual plies need to deform in those regions where the neighbouring plies can only undergo a limited amount of deformation, due to the higher stiffness in these areas. The compressive stresses, which come forth out of the shear motion, are transferred to the neighbouring ply. Here they induce wrinkling in the region where the deformability is low. Increasing the relative orientation from 0 to 45° increases the distances between the high deformable zones of each ply, thus wrinkling is more pronounced.

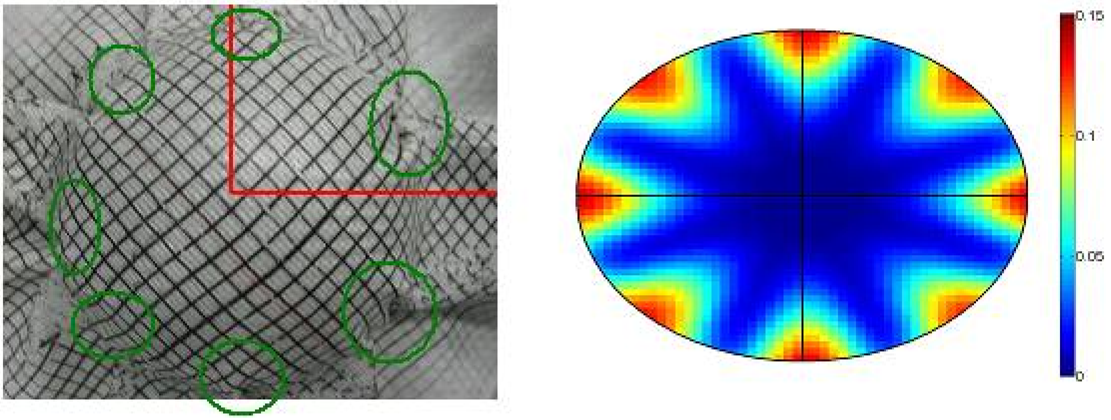


Figure 9. Comparison between the local difference in displacement and the deepdrawed laminate for 45° relative orientation with a 0.5 mm PP-sheet between the plies

Figure 9 shows the comparison between a 45° laminate where the interlayer thickness is increased and the local displacement plot. The regions where wrinkling occurs still agree with the areas where the difference in local displacement is the highest. Though, the amount of wrinkling decreases since a lower friction coefficient decreases the transfer of compressive stresses to the neighbouring ply.

CONCLUSIONS

The formability of two-layered thermoplastic reinforced fabric laminates with different fiber orientations is investigated. A forming limit diagram is presented, which visualizes the formability of multi-layered fabric laminates. A decrease in formability is characterized by a decrease in in-plane shear and an increase in wrinkling of the laminates.

It is found that the amount of wrinkling strongly depends on the fabric lay-up inside the laminate. Increasing the orientation between the yarns of the different plies decreases the formability. Intraply shear triggers wrinkling much faster when the orientation between the plies increases. The shear motion develops local compressive stresses in the neighbouring ply. Due to low deformability of the neighbouring ply in the area where the compressive stresses are invoked, wrinkling occurs. When the relative orientation increases, the region of the neighbouring ply where compression takes place becomes less deformable and thus wrinkling is more severe.

Increasing the interlayer thickness makes each ply deform more independent, the interaction with neighbouring plies is reduced. The motion of intraply shear invokes less compressive stresses in the neighbouring ply, which reduces the amount of wrinkling.

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