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Robotic Die-Less Forming Strategy for Fiber-Reinforced Plastic Composites Production

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Abstract

Fiber-reinforced plastics (FRP) production in many cases involves expensive molds, which especially hinders cost-effective production of small series and prototypes. In metal parts production, incremental sheet forming (ISF) is an established process for creating individual parts and small series through a flexible and die-less process. Establishing a similar process for FRP is desirable but challenging, as deformation mechanisms of endless FRP differ significantly from metal sheets. Using just two movable standard tools, bending and shear of woven fabric needs to be realized. Thus, determining feasible forming paths of the robot guided tools for the desired geometries is one of the biggest challenges. In this paper, we propose a forming strategy for highly automated and flexible die-less FRP production based upon the theoretical background of draping mechanisms. We investigate the strategy in a basic experimental setup, generating a hemisphere and tetrahedron.

Keywords: Fiber-reinforced plastic; Composite material; Die-less forming; Free-forming; Robotic forming; Draping

1. Introduction

The usage of fiber-reinforced plastics (FRP) increased significantly over the last years due to their high structural strength-to-weight-ratio. A common manufacturing process for thermoset polymer composites is injection molding, where dry reinforcement fabric preforms are placed in a mold. After the mold is closed, resin is injected and the part is cured. Hand-layup is a manual process for smaller series, where dry fabric is placed on an open mold and resin is applied and compacted with a roller. Thermoplastic FRP are commonly shaped using thermoforming, where the preheated sheet is placed between two heated molds by grippers. As the molds close to form the final part geometry, the grippers may introduce tension into the laminate to improve formability [1]. Since design and fabrication of the required molds is time-consuming and costly, respective FRP-production processes are not economically suitable for prototyping and small batch production. However, increasing cost pressure, higher variant diversity and the demand for shorter development times require new flexible manufacturing processes with reduced tooling-effort [2].

Incremental sheet forming (ISF) of metals is an established process for generating different geometries out of a flat sheet using one or more universal tools. These usually hemispherical tool ends or roller balls are moved along a variable tool path by CNC-machines or industrial robots, progressively forming the workpiece layer by layer. As the sheet is clamped by a blank holder, local deformations are introduced as strains. Different process variants include single-point incremental forming (SPIF) and double-sided incremental forming (DSIF) using two tools, one on each side of the sheet. While metals are dominant in ISF, forming of thermoplastics is still at an early stage [3,4].

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Due to the benefits of ISF, researchers tried to apply it to the forming of FRP such as pre-impregnated fabric or pre-consolidated continuous-fiber-reinforced thermoplastic sheets (organo sheets). However, direct application failed and metal sheets were added to the fabrics in order to maintain the deformation, producing more or less acceptable results [5–7].

To conclude, few flexible FRP forming processes and no ISF process without a metal sheet as support exist because of the lacking stability and markedly different deformation mechanisms of woven fibers. With high tensile strength and limited strain, a significant elongation of the fibers is not possible [1]. Instead, fiber bending and shear as the main draping mechanisms must be realized not only in the forming spot, but also in adjacent regions of the fabric, while maintaining already generated final part geometries. Thus, existing algorithms for metal ISF tool path generation [8] are not applicable and a feasible forming strategy for die-less FRP forming processes needs to be developed.

In the following, the draping mechanisms of woven reinforcement fabric are described and analyzed. We then briefly outline our newly proposed die-less FRP forming processes. The resulting forming strategy including forming sequence, starting point and clamping conditions is formulated, investigated in a basic experimental setup and finally discussed.

2. Draping of Woven Reinforcement Fabric

2.1. Draping mechanisms

Draping of flat textile into a three-dimensional shape is achieved by realizing the mechanisms of shear and bending, to a lower extent fiber displacement and textile stretching caused by fiber straightening as well as very limitedly fiber elongation [9]. Figure 1 illustrates the individual mechanisms.

Developable surfaces such as flat or singly curved surfaces only require fiber bending for draping. On the other hand, un-developable surfaces with double curvature require in-plane deformation, which in case of woven fabrics especially means shearing of the initially rectangular thread systems, the warp and weft yarns. The individual fibers rotate about their crossing points, thus changing the included angle. However, the amount of shear achievable in a fabric is limited by its so-called locking angle. If it is exceeded, the material bulges and wrinkles develop, introducing defects in the final component [9–11].

2.2. Draping process

Automated solutions for composite draping in processes such as thermoforming exist, for example using active modular grippers applying tension to avoid wrinkling [12]. However, regarding versatility and the capability of draping complex geometries with double-curvature, hand-layup by skilled workers is still unchallenged and very commonly used [13,14].

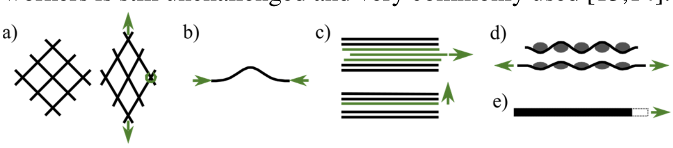

Fig. 1. Draping Mechanisms: a) Shear, b) Bending, c) Fiber Displacement, d) Textile Stretching, e) Fiber Elongation

Elkington et al. analyzed and classified the performed actions in manual hand-layup of woven fabrics onto complex molds. Of most interest here are the three defined shearing techniques: applying tension through grasping the fabric at two different points, applying tension by securing a point of the fabric on the mold and grasping another point, and pushing the fabric into a concave tool area while keeping the already draped edge of the recess secured [14]. While the former two techniques shear the material in a larger area (up to the whole fabric) relatively evenly before applying it to the mold, the latter follows a rather concurrent and local approach.

It can be further distinguished in the direction in which the tension is applied to induce shear. As depicted in Figures 2a and b, locally applying load in fiber direction yields a non-uniform deformation, while loading in bias direction results in equal deformation of warp and weft tows [10,14].

2.3. Draping simulation

For the prediction of the final fiber orientations and other characteristics, draping can be simulated using mechanical or kinematic models. While advanced mechanical finite element analysis may incorporate numerous physical phenomena in a dynamic and nonlinear analysis, simple kinematic draping simulations yield fast results in determining the general drapability and final shear distribution of the part [15,16].

In kinematic simulation, the fabric is modeled as an initially orthogonal grid of pin-jointed equal-sided cells with the joints representing the warp/weft intersection points of the woven textile. Assuming inextensibility of the fibers and zero shear stiffness as well as no fiber slippage at the pivot points, the points are fixed to the desired surface one after another while shearing the cells [10,15–17].

Initial constraints are necessary as an infinite number of draping solutions is possible. Most important constraint is the starting point of the draping, which is the first contact point of the fabric and the mold. Furthermore, the initial draping direction is to be set, representing the fiber orientation relative to the mold. Traditionally, this direction is used to generate two initial paths on the mold surface, the so called constrained paths, which can be set as geodesic lines. The paths in warp and weft direction intersect in the starting point, forming a cross on the surface and dividing it into independently drapable quadrants, as depicted in Figure 2c. The remaining node points are then uniquely set on the surface following the assumptions above. Iterative optimization of the constraints is possible, for example minimizing the shear angles [10,15–17].

Different and more advanced approaches for kinematic draping exist, such as the minimum energy criterion. As the mesh grows one unit cell in each direction, the individual fiber directions are set to minimize the total required shear energy for that step [10,16].

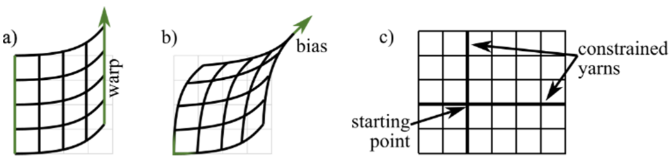

Fig. 2. Tensioning in a) warp- and b) bias-direction, c) starting point, constrained yarn paths and quadrants for kinematic drape simulation

3. Robotic Die-less Forming of FRP

The basic manufacturing steps of FRP are impregnation of the fibers with resin, shaping of the structure, consolidation and curing or solidification, followed by eventual post-processing. Either, the final component geometry and the composite material are produced at the same time using dry fibers and initially separate matrix, or semi-finished products, fibers already impregnated with matrix (prepregs), are used. While thermosets are no longer formable after curing, thermoplastics can be softened and reshaped with the aid of heat [1].

In the joint research project "iFish", several possible die-less FRP forming and production processes are conceptualized and investigated. The aim is to realize forming of 0°/90° woven fabrics with two individually robot guided tools such als rotating balls or rollers, comparable to DSIF but without the use of metal support sheets. The following process alternatives, published in detail elsewhere, shall be briefly outlined:

The forming of organo sheets requires localized heating for example by infrared light or induction in order to acquire formability. Immediate cooling of the forming spot must be realized using cooled tools or an air jet to maintain the shape.

Dry fabric can be locally impregnated with photopolymeric thermoset resin which is then cured using UV laser light.

Another option is the processing of woven commingled yarns out of reinforcement fibers and thermoplastic polymer fibers. After locally melting the polymer and impregnating the reinforcement fibers with matrix, the forming spot is consolidated, cooled and solidified. This can be achieved by a small robot guided heated press, adding one solidified area on another, or continuously forming with rollers as depicted in the concept sketch in Figure 3.

Similar approaches with localized pressing tools might be feasible for dry fabric and initially separate thermoplastic or thermoset matrix, albeit more complex impregnation.

The absence of a mold requires extra effort in handling and clamping the fabric. While cold organo sheets are stable and rigid, sheets with moldable matrix or dry fabrics are flexible and will deform in possibly undesirable ways if not clamped sufficiently, being detrimental to the success of the following draping operations. At the same time, the clamping must allow fibers to move and flow to the local deformation point or the edge in order to realize bending and shear. This also requires that all areas to be formed and those from which fiber material is pulled or into which it is pushed must be heated in the case of organo sheets and not cured in the case of dry fabrics. However, once solidified or cured, the already formed area maintains its shape, so that no extra securing as in manual layup is required for forming adjacent areas.

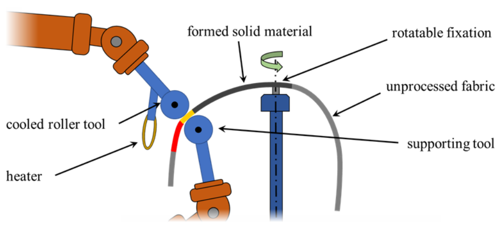

Fig. 3. Concept sketch of die-less commingled weave processing (forming, impregnation, consolidation) using two individually robot-guided roller tools

4. Forming Strategy

4.1. Starting point

As a first step in acquiring the forming sequence on which the tool paths will be based, a kinematic draping simulation of the desired part geometry with the used fabric needs to be carried out. The mesh size should be set at least a little smaller than the width of the practical forming area of the tool, so that there is a slight overlap in the tool paths. The starting point and the initial fiber direction should be numerically optimized regarding the general requirements stated above, especially minimizing the amount of shear and distributing it as equally as possible around the starting point, as the shear adds up with increasing curvature moving away from it. For many geometries with high symmetry such as the hemisphere, the choice of the starting point is intuitively right, namely in the highest point which equals the point of symmetry [16].

At best, the orientation of the initial warp and weft yarns should be chosen so that they do not require any in-plane deformation while forming, facilitating the die-less process. The kinematic simulation should therefore make use of the geodesic constrained paths approach.

Results of the simulation are the optimal starting point and initial fiber orientations as well as the final alignment of the fibers with the required shear angles.

4.2. Overall strategy

The required shear distribution is the key characteristic to consider when determining the order of shaping. In general, it is reasonable to start forming – in this case bending – and solidifying the areas not requiring in-plane deformation and subsequently working up to the areas that need to be sheared the most. This prevents hardly reversible in-plane deformation in areas where no shear is required or desirable, as surrounding areas also deform when shear is introduced.

Two approaches were considered to determine the order of shaping, which in this work are referred to as the *path forming principle* and the *layering principle*, shown in Figure 4 for a hemisphere in top view. It is important to note that for both principles, the part geometry should be oriented in a way that the main curvature of the surface is oriented towards gravity, so that gravity is not contrarily shaping the flexible fabric.

The *path forming principle* is based upon the constrained paths approach in kinematic simulation. Originating at the starting point and moving to the edge, the constrained paths requiring no or the fewest in-plane deformation are formed and

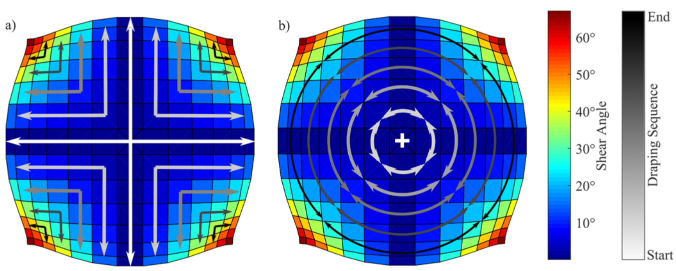

Fig. 4. Kinematic simulation results of a hemisphere in top view with forming sequence according to a) path forming principle and b) layering principle

solidified first. Subsequently, paths to be formed on each side next to the constrained paths along the desired fiber orientation obtained from simulation are added to a stack. The path which requires the least cumulative shear is then formed from the rigid area to the edge of the fabric and another path next to it is added to the stack. The process of forming the path with least required shear and adding a new path to the stack is repeated, until the whole geometry is formed.

In contrast, the *layering principle* is inspired by the minimum energy criterion of the kinematic simulation. Here, the forming is advanced growing one unit cell in each direction from the starting point. In the case of simple symmetric geometries such as the hemisphere, forming is done layer by layer according to the contour lines, as it is shown in Figure 4. Within each layer or forming step, the cells are formed and solidified after another from least to most shear.

Theoretical considerations result in various advantages and disadvantages of both presented principles. In the *layering principle*, areas of the next layer that require little or no shear could already be irreversibly sheared either by forming of sheared cells in the previous layer or due to the fact that a big area of flexible fabric remains unsupported. However, stability of the already formed area is higher due to the fact that it is connected throughout. The *path forming principle* facilitates forming by dividing the fabric into individually drapable quadrants through the constrained paths. Once formed and solidified, the constrained paths can add a certain stability to the flexible fabric. Furthermore, the problem of introducing undesired shear is at least minimized, if not avoided. For these reasons and after preliminary tests, the *path forming principle* is selected for further considerations.

4.3. Fixation & shear introduction

Resulting from the meaning of the starting point as origin of the desired fiber deformations, it must be securely fixed and rigid in an area of at least the size of the forming tool, depicted in Figure 5a. Additional support for example by clamping on the edges is required in the case of dry and flexible fabric in order to prevent it from deforming in unpredictable ways prior to forming. This clamping is to be maintained right until movement of the respective fibers is required for draping. Once the constrained paths are formed and rigid, overall stability of the fabric should be high enough but could be further increased by locally clamping its cured edges, if necessary.

Following the path forming principle as in Figure 5b, a local forming approach similar to concurrent local shearing in hand-layup is responsible for the introduction of shear into the fabric. Shear is mainly generated and driven by moving the tools along

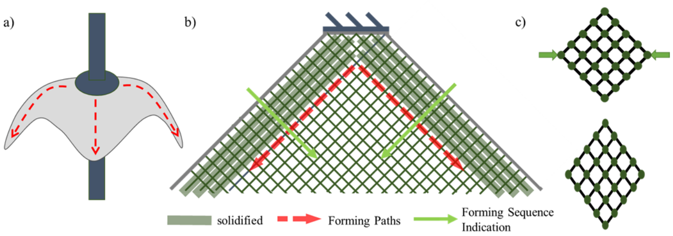

Fig. 5. a) Fixation, b) Path Forming Principle, c) Shear Introduction Model

the desired surface geometry in paths running right adjacent to an already rigid area of the part. As pictured in the pin-joint model in Figure 5c, in order to produce a curved geometry, the distance between the diagonally opposite newly fixed nodes shortens, introducing compressive stresses into the fibers in between the rigid areas. These are readily relieved by shearing or out-of-plane deformation. If, depending among others on the shear and bending stiffness of the material, the latter effect predominates, undesired wrinkles develop instead of the desired shear.

However, small amounts of initial out-of-plane deformation might be tolerable and reversible in the next forming step, as bending and shear are not the only mechanisms prevalent in draping. Although not accounted for in the classical pin-joint net model, folds along the diagonals of the warp/weft-mesh are equally possible as a certain amount of fiber sliding. As a consequence, even with three points of a mesh being fixed, further or less shear in the other half of the cell is possible and the fourth point can conform to the desired surface, preventing wrinkles. This also explains why in practice, shear is not fully propagated until the fabric edge but decreases with higher distance from the forming point, depending on the float.

If the tool movement is able to introduce tension in fiber direction between the solidified area and the forming spot, further deformation is possible to a limited extent due to the stretching of the fabric, straightening the woven fibers. This stretching is very locally bending the fibers perpendicular to the forming direction in-plane, resulting in shear. All mechanisms together explain the basic principle of the formation and propagation of shear in the *path forming principle*. For more complex geometries with multiple starting points with a certain distance between each other, multiple (sequential) fixations are required in order to minimize torsional moments on the part and to offer enough stability for forming.

4.4. Additional considerations

For the forming of organo sheets, it must be ensured that areas which require fiber movement are heated, enabling deformation of the matrix. In the case of forming paths with pure out-of-plane deformation such as the constrained paths, the fibers in the forming path or even just the forming point need to deform as well as the whole area perpendicular to the bend from edge to edge of the fabric. Once the constrained paths are formed, heating is required only in the actual quadrant being shaped. For introducing in-plane deformation such as shear, the fibers in the forming path from start to the edge require motion as well as all fibers crossing this forming path from the path to the edge. This is also the direction into which the shear is introduced. Thus, as forming progresses, areas to be heated are getting smaller and smaller as shown in Figure 6.

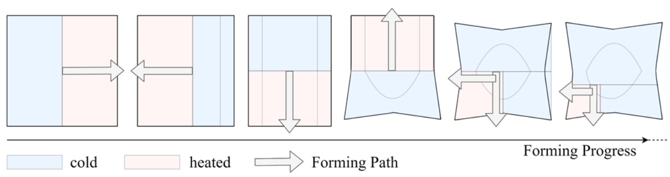

Fig. 6. Organo sheet heating and forming progress (up to first quadrant)

The approach of choosing the forming path with least shear to be formed next will ensure a relatively symmetric forming for symmetric parts, also meaning an even forming around and towards the area with most shear. If two possible forming paths exhibit an equal amount of shear, priority should be given to the one with most symmetry to the already formed geometry. This is especially important when forming the constrained paths, as asymmetry can cause the fabric to shear. After forming the constrained paths, each quadrant of an organo sheet can be fully formed after another individually due to the high stability of the solid sheet. In contrast, symmetric forming of dry flexible textile, ensuring an even weight distribution with respect to the fixation, is quite important for stability reasons, preventing undesired displacement and shear. For parts with less symmetry, a simulation or approximation of the weights and balances can be considered as criterion.

In order to reduce production time, movement of the tools without actually forming should be minimized. However, this third criterion should only come into effect if the first two do not yield a clear result of the forming sequence. An additional condition, which especially comes into effect when forming the constrained paths, would be to shape the path with the lowest out-of-plane curvature first.

4.5. Forming sequence flow chart

Figure 7 depicts the developed forming strategy as a flow chart diagram. Only a single starting point and fixation was considered for simplicity, thus not being valid for complex parts with multiple protrusions or recessions.

In the case of organo sheets, after shaping of the constrained paths, the stack can be divided into individual quadrant stacks, thus forming each quadrant individually. In the flow chart, this condition would be checked at the asterisk-mark.

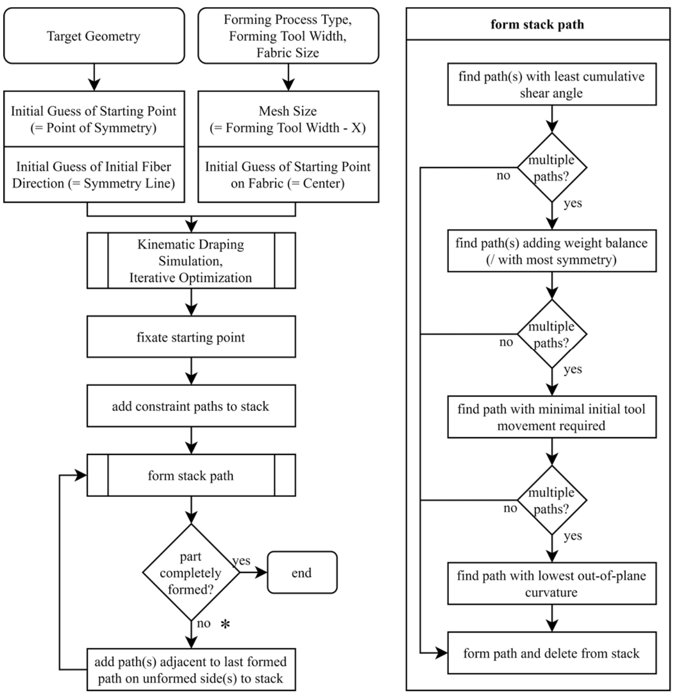

Fig. 7. Flow chart diagram of the developed forming strategy

5. Practical Investigation

5.1. Experimental setup

In order to prove general feasibility of the forming strategy and of introducing shear only by compression through out-of-plane deformation, dry glass fiber fabric in twill weave with a areal weight of 160 g/m^2 was used and fastened with pins on a cork hemisphere with a diameter of 20 cm and a Styrofoam tetrahedron with edge lengths of 24 cm. The hemisphere is commonly used in science due to the double-curved surface and highest possible symmetry. The tetrahedron with just uniaxial symmetry is more challenging. It was modified by flattening the tip to better fixate the starting point. A grid with a spacing of 1.5 cm was drawn on the flat fabric in order to enable following the forming paths in fiber direction and to visualize the resulting shear distribution. The fabric was fixed to the molds in each grid node according to the forming strategy, applying pressure only on the forming point and not pulling on the fabric.

In order to investigate applicability to the actual die-less forming processes, the same fabric with a size of 30 x 30 cm^2 was centrally fixed to a pole with the remainder hanging freely. Forming paths of a hemisphere were followed manually using a handheld tool on the lower side while locally applying UV-sensitive thermoset resin and curing it with laser light on the upper side of the fabric.

5.2. Results

The paths and sequences for forming a hemisphere and a tetrahedron are shown in Figure 8 and corresponding draping results are depicted in Figure 9. In the case of the hemisphere, evenly distributed shear was successfully introduced without applying tension and no wrinkles appeared during the forming process. For the tetrahedron however, the simulation predicts high shear angles and localized steep shear gradients. In practice, wrinkling occurred relatively early in the process as pressing on the grid points only did not introduce sufficient shear to map the geometry. Pulling on the fabric edge after the trial lead to increased shear and reduced the wrinkles to a certain extent (not displayed in Figure 9).

The result of die-less forming and resin curing is depicted in Figure 10. Adequate shear was introduced to form a hemisphere, although not of perfect shape due to the flexibility of the fabric and the mostly manual process. However, the forming sequence symmetric to the starting point enabled a uniform weight distribution and sufficient stability.

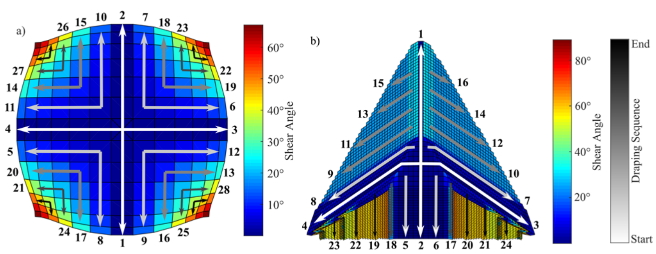

Fig. 8. Resulting forming sequence for a) hemisphere and b) tetrahedron

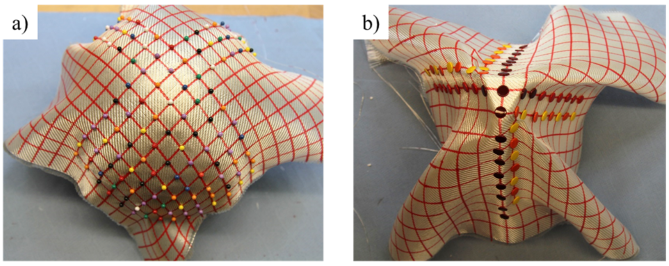

Fig. 9. Results of draping a) a hemisphere and b) a tetrahedron, using glass fiber fabric and pins to fixate the fabric according to the forming strategy

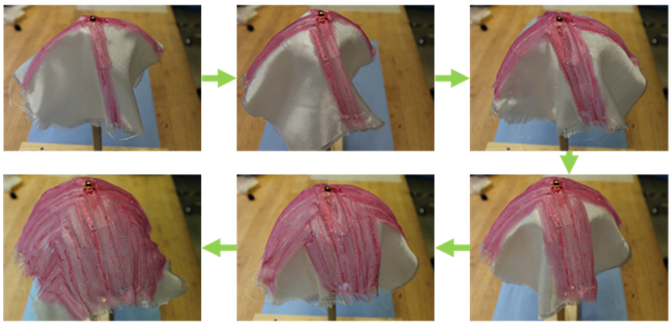

Fig. 10. Forming sequence and result of die-less forming of a hemisphere using glass fiber fabric and red UV-curable resin

6. Summary, Discussion and Outlook

With the proposed forming strategy for die-less FRP production, forming paths and their sequence can be generated on which robot tool movements are to be based. The paths, following the required fiber directions, and the corresponding shear distribution as the main sequencing criterion are obtained from a kinematic drape simulation of the desired geometry. Clamping conditions were designed and a heating strategy for organo sheet forming was developed, allowing just the fiber movement required to realize necessary draping mechanisms.

The practical trials show that a certain amount of shear can be introduced into the fabric by compression through out-of-plane deformation. This was not only the case in the initial tests using molds, which prevent fiber buckling in mold direction, but also in the die-less forming test, where gravity promotes compressive stresses being relieved by out-of-plane instead of the desired in-plane deformation. However, the exact limits of the proposed technique as shown while forming the tetrahedron need to be quantified in further investigations. The results will heavily depend on the materials used, especially on the ratio of shear and bending stiffness. Woven fabric with higher float as in the case of satin weave has higher drapability than twill or plain weave. However, as displacement stability decreases, unwanted draping and therefore deviation of fiber orientations during handling and forming increase [11]. Additionally, the effect of the tools' normal force on the fabric in the actual process implementation, introducing a certain amount of tension in fiber direction when moving, is to be analyzed.

Pulling on the fabric further away from the forming spot in bias direction would offer the possibility of introducing shear more globally, possibly aiding in acquiring higher shear angles and suppressing wrinkles. However, it would be complicated to determine the exact amount and direction of the needed tension, requiring exact FE simulation and optimization of each forming step. In general, FE simulations accounting for the influence of the matrix material on drapability would be beneficial, especially in the case of organo sheets.

A feedback loop concerning dimensional accuracy and acquired fiber orientations could be implemented to further improve the process. For complex parts with different geometric features, a feature-based approach with individual forming strategies for each feature is to be considered.

Acknowledgements

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