A HYBRID KINEMATIC-BASED MODEL (HYKE-I) FOR PREDICTING FORMING-INDUCED DEFECTS OF WOVEN COMPOSITES

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ABSTRACT

This article is part of a research program aiming at a new hybrid modeling framework to predict the forming pattern of woven fabrics over 3D surfaces, with an emphasis on capturing defects during stamping and vacuum bagging operations. It has been well recognized that trellising shear is the primary mechanism allowing the woven fabrics to conform to doubly-curved geometries. Although the kinematic draping models developed based on this mechanism serve as a decent approximation to predicting shear angles, they lack full fidelity as they do not account for tooling conditions, mechanical loads, fabric properties, and processing environment. At the other extremes are the inclusive finite element-based forming models which include all the material properties as well as interactions of the reinforcement with the tool and processing conditions. However, such models are not always computationally affordable and also some input parameters are difficult to characterize. The first version of the hybrid model (termed HYKE-I) proposed in this paper attempts to take an intermediate approach between the two above extremes, yielding computational cost that is lower than the full-scale FE modeling, without scarifying much accuracy. Its applicability has been illustrated via benchmark hemisphere forming examples. In essence, the model introduces the idea of effective seed point (ESP) and the seed direction under kinematic mapping based on the applied boundary conditions via the blank holders, and subsequently predicts the fabric's local deformation features by taking into account its mechanical properties.

1 INTRODUCTION

Woven fiber-reinforced polymers (WFRP) are composite materials consisting of strong interlaced fibers, dispersed into a continuous lightweight matrix. Due to their superior strength-to-weight ratios, impact resistance, and the ability to be shaped for performance-based design, along with low manufacturing costs, WFRP composites are now among top materials of choice in such sectors as aerospace and automotive [1-3]. These advantages can be, however, compromised by potential forming defects, particularly in producing sensitive parts such as aerostructures [4].

Composite components fabricated using prepreg technology are normally more expensive than their dry fiber counterpart; yet the former is often favoured by the aerospace industry due to the higher part quality. Nonetheless, forming of prepregs or dry woven fabrics onto complex, doubly-curved shapes has remained a challenge for manufacturers, owing to possible in-plane and/or out-of-plane defects such as fiber waviness and wrinkles [5, 6]. These defects are detrimental to the final structure's integrity; for instance, a through-thickness strength reduction greater than 50% and the tensile and compressive strength reductions up to 30% have been observed [7]. Wrinkles can both initiate from defects present in the as-received reinforcement, or be intrinsic to the selection of design and manufacture parameters; e.g., the complex part geometry, ply sequence, cure and pressure cycle in the autoclave, etc. [8]. Having a swift and reliable simulation tool, capable of simulating the fabric forming process and flagging up scenarios that lead to deformation defects, can have enormous use to save computing overheads and permit *first-time-right-design*.

Over the last decades, modelling, simulation and optimization of composite manufacturing processes have received extensive attention by researchers, with the objective of improving the final part quality, while lessening the production time. However, such computational tools still receive limited acceptance in most industries, mainly because of their complexity, time consuming and experience–demanding nature [9]. Focusing on simulation of fabric reinforcements, the kinematic draping models have served as a decent means to the approximation of shear angle distribution in the draped form, yet they lack fidelity to predict such defects as wrinkles, as they do not account for tooling conditions, mechanical loads, fabric properties, and processing parameters [10, 11]. The initial contact point (termed as seed point) and the drape direction (knows as seed direction) are two important parameters in the kinematic models, and the final drape pattern significantly depends on these parameters. As a result, infinite drape pattern solutions can emerge by selecting different seed points or seed directions [10, 12]. After specifying these parameters along with the fabric spacing, the grid points upon draping are obtained by using the intersection of the starting yarn segment with the tool surface. Subsequent locations of crossover points are calculated using the previously constrained grid points and the mapping of the free sections of the fabric onto the mould surface [10]. It has been shown that manipulating the seed point can lead to more realistic results e.g. based on the direction of stamp in the thermoforming process of fabric, or in the direction that the laminator (operator) sweeps the plies onto the mould [13]. Yet to date, there has been no clear guideline as to how the latter techniques should be accurately implemented using the existing kinematic models.

At the other extreme are the inclusive finite element-based (FE) forming models that consider the full interaction of the reinforcement with the tool, change in tow waviness, lateral compaction, forming loads, and processing conditions. However, such models are not computationally affordable to most industries [6]. In addition, an accurate calibration of parameters such as fabric mechanical properties, tool-ply and ply-ply friction is required. Although the FE-based approaches overpower many of the challenges associated with the kinematic models, they demand substantial computational power (e.g. a large-scale FE analysis of forming might take a few hours to run, compared to the seconds taken by a kinematic model).

Recognizing the above state of fabric simulation conundrum and at the same time the industrial need for fast design solutions, this research seeks to develop a new *hybrid* model to predict the forming behavior of woven fabrics, with an emphasis on capturing out-of-plane defects and fiber waviness during stamping or vacuum bagging forming operations. The sections to follow begin with a description of the set-up used for kinematics and FE based models, as well as a new insight on how changing the location of initial contact point in the kinematic model can lead to realistic predictions. Subsequently, the hybrid modelling framework is presented, followed by validating it against an experimental forming trial.

2 MODELING FRAMEWORK

2.1 Kinematic model: The effect of seed point and seed curve

A typical kinematic model enables simulation of woven fabric forming over a mould surface using an 'advancing front' approach, starting from an initial contact point (seed point) between the fabric and the mould and the initial fiber direction (seed curve) [14]. These initial constraints significantly alters the final shear pattern of the reinforcement. Since the fabric stiffness and loading conditions are not taken into account in the kinematic models (as they are based on a pin-joined-net), it is assumed that the neighboring fibers are not restricted by external membrane forces imposed from the blank holders. Accordingly, the difference in the deformation gradient caused by e.g. an uneven distribution of blank holder forces is neglected when draping beings at the peak point of the mould surface. In the latter case, a precise solution is obtained only when the part geometry is axisymmetric and the boundary conditions in the real set-up are uniform [14]. Figure 1 depicts a hemisphere mould geometry along with different seed points and combinations of clamping conditions. It has been experimentally shown that applying high clamping forces would restrict the “flow” of the shear deformation, leading to less deformed areas nearby the clamps with higher forces [15]. On the other hand, less controlled fabric areas conform to the geometry of the mould with more freedom, which in turn leads to an asymmetric shear gradient across the final part. For the case of uneven boundary condition, it will be shown in Section 3 that changing the location of the seed point along a resultant vector of blank holder forces (Figure 1) can be a useful means to obtain realistic shear results when using kinematic models.

2.2 Full FE-based model

2.2.1 Material model

*FABRIC is a phenomenological model built in ABAQUS® EXPLICIT in which the planer kinematic state of the fabric reinforcement is defined in terms of strains in the fabric’s plane along the two structural directions, as well as the change of angle between them, known as the shear angle. The *FABRIC material model in the present work was implemented using test data from a 5.78 Oz/yard 3K carbon fiber plain weave. Namely, the uniaxial tensile test data along weft and warp directions, as well as the in-plane shear test data using bias extension experiment were employed.

2.2.2 Simulation setup

Figure 2 shows the configuration used in the initial forming simulation. The punch, die and blank holder were modeled as analytical rigid bodies (Figure 2). Two examples of blank holders, namely full round and half round, weighting 0.5 Kg and 1Kg, respectively, were laid on top of the fabric, while a uniform clamping force of 1000N was additionally imposed during the course of forming in both examples. The 4-node shell elements (S4R) were used to capture the behavior of the single-layer plain weave with an orientation of [0/90] with respect to the blank holder edge. The transverse shear stiffness of the shell elements was set to be 10 MPa. The punch was specified to travel in the vertical direction for 80 mm in 25 seconds. The mesh direction was aligned with the material structural orientations. A linear penalty method was reinforced to the tangential contact between the fabric, die and blank holders, with an isotropic coefficient of friction of 0.2.

2.3 Hybrid kinematic model (HYKE-1)

Expectedly, a full scale FE model should be more accurate than a kinematic model in evaluating fabric’s formed pattern, as ply stiffness and boundary conditions as well as frictional contacts are taken into account in the former model. For instance, an unbalanced fabric accommodates the mould shape differently than a balanced fabric, while a conventional kinematic model does not recognize such difference. Moreover, when draping from a peak seed point, the kinematic model implicitly assumes an even blank holding pressure distribution across the fabric edges. Nonetheless, the power of the kinematic models in obtaining a good first-order approximation in a fraction of a minute cannot be disputed. If the advantages of both FE and kinematic methods are exploited together, a decent intermediate forming model can be developed [9]. This is the main driver of the hybrid forming model (named HYKE-1) in the current work.

HYKE-1 simplifies the forming procedure by utilising the shear angle solution provided by the kinematic model as a first-order approximation, and then by adding the contribution of fabric material properties, the shape and location of local defects may be captured. Figure 3 shows the overview of the proposed numerical framework for HYKE-1. The sequence of steps in the model is as follows:

1. Start with a kinematic model and optimally choose the effective seed point and seed curve, mimicking the actual deformation flow arising from an even or uneven blank holding boundary condition.
2. Drape the fabric on the given geometry in the kinematic model environment. In this work, Interactive Drape® software [16] was used.

3. Extract the final coordinate of each cross-over point from the kinematic model using a MATLAB® script.
4. Create finite element mesh in ABAQUS® FE and assign the obtained coordinates from step 3 to each node on the flat fabric, and run the analysis without modeling the punch, die and blank holders.

3 RESULTS AND DISCUSSION

3.1 Comparison of kinematic and full FE model: effective seed point verification

Figure 4 shows the plot of shear angle for the formed plain weave using the kinematic approach. The seed point was selected to be at the highest point on the mould surface (i.e., considering a fully symmetrical forming set-up for this first example). Upon draping, the shear distribution was symmetric across the mould sectors, with a maximum shear angle of 40°. The obtained shear distribution was in good agreement with the results reported in [15]. As discussed in Section 2.1, the kinematic modeling approach faces challenges in cases where the part geometry is not axisymmetric or uneven blank holder forces are imposed around the fabric boundaries. A possible remedy is to change the location of the seed point so that the resulting shear plot mimics the forming pattern realistically. Figure 5 shows the result of kinematic model examining this idea, along with a comparison to the full scale FE model. In this example, as an extreme case, a half round blank holder (Figure 2) was laid over the single layer fabric, hence significantly changing the distribution of tensile forces imposed by blank holders on the ply extremities and causing wrinkles. As revealed in the FE model results, the shear distribution shifts towards the less restricted area of the fabric, leaving the constrained half less deformed. In order to obtain a similar drape pattern using the kinematic model, the location of seed point was moved towards the fictitious resultant vector of global tensile forces. The shear plot in Figure 5 suggests that initializing the drape from such a different location (hereafter referred to as the effective seed point or ESP) leads to formation of a realistic shear pattern. The restriction caused by fixing the seed point off-center, has forced the fabric in the kinematic model to accommodate higher shear angles at the far-left end of the geometry, which corresponds to the more unrestricted region of fabric.

To further validate the idea of the ESP, another experimental forming trial with an uneven and 'discrete' clamping condition was conducted (Figure 6). The backlighting technique developed in [15] was used to measure the shear angles using image analysis. As displayed experimentally in Figure 7, the deformation gradient across the fabric regions has been highly affected by the uneven forces applied to the ply boundaries. Accordingly, in the kinematic model, *the location of the effective seed point can be shifted from the top point of the mould surface to a new location defined by the resultant vector of blank holder forces. Note that theoretically, the shear angle at the seed point is zero (no deformation). As depicted in Figure 7, the fabric tends to accommodate the shear flow based upon the level of restriction imposed from the boundaries, with the less restricted fabric areas undergoing larger shear deformation.*

3.2 Verification of HYKE-1 model

The hybrid modeling approach was verified for the discrete blank holing example with the uneven pressure distribution as shown in Figure 6. The aim was to exploit both the speed and simplicity of the kinematic model while appending it with the accuracy of the FE analysis. The fabric sample (200 mm × 200mm) was draped onto the hemisphere shape, starting from the ESP. For this simple simulation, the run time of HYKE-1 was 47 seconds, as compared to 140 seconds for the full FE model. It was found that the test data-based *FABRIC material model approximates the shear angles with sufficient accuracy (Figure 8), and the shear deformation provided by the HYKE-1 model is in good agreement with the actual draped pattern seen in Figure 7.

4 CONCLUSIONS

This article briefly reviewed some advantages and limitations of the current fabric forming simulation models, from both basic research and industrial viewpoints. A potential remedy was proposed to modify the solutions obtained from the kinematic model when draping the dry fabric/prepreg over unsymmetrical shapes or under uneven blank holder pressures. Namely, for the case of hemisphere, it was shown that an effective seed point (ESP) can be obtained along a resultant vector defined by the uneven blank holding forces. Combining this feature under the conventional kinematic model with the advantages of FE-based analysis led to development of the hybrid model, which may be viewed as an intermediate solution between the very fast and the very accurate modeling approaches. The first prototype of this model (HYKE-1) was presented and verified against a simple forming trial. The intent is to develop different versions of this hybrid model by progressively adding the levels of complexity into the analysis, which eventually will allow designers to choose the best compromise between the speed and accuracy, depending on the objective of a given forming simulation (e.g., estimation of the draped shape/shear angles, location of wrinkles, or the exact size of wrinkles, ply sliding, etc.).

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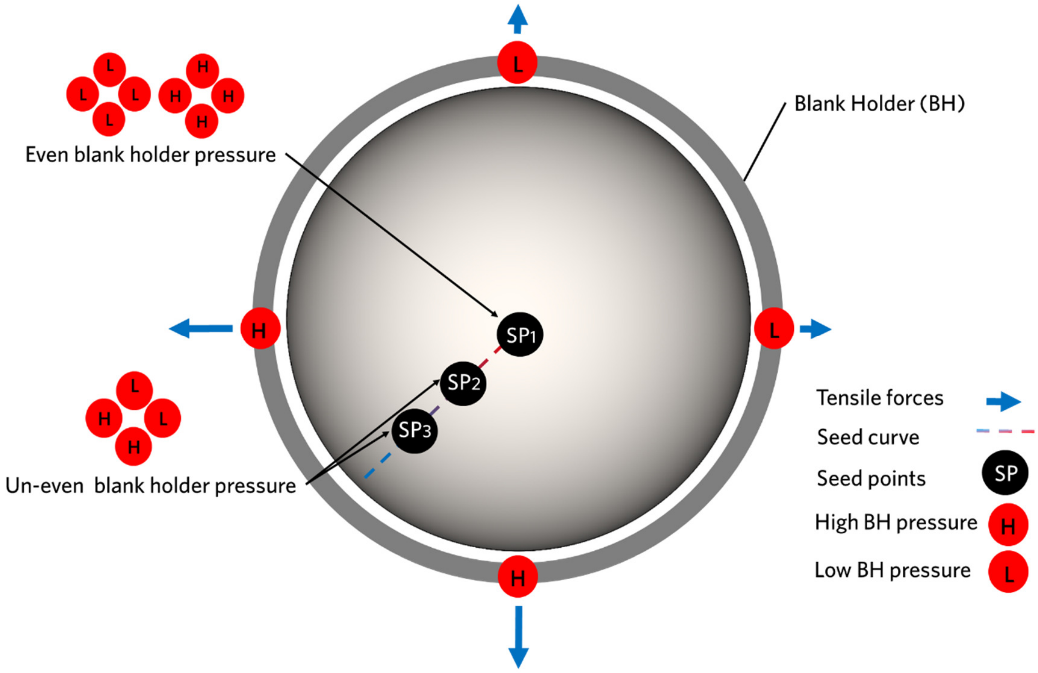

Figure 1. Example of determination of the effective seed point in the kinematic model. SP1 corresponds to the effective seed point when the blank holding pressure is evenly distributed (i.e., all clamps with low or high pressure). When the blank holder pressure distribution is uneven, the seed point can be moved along the resultant force vector shown as dashed line. The blue arrows represent the magnitude of applied force in each blank holder.

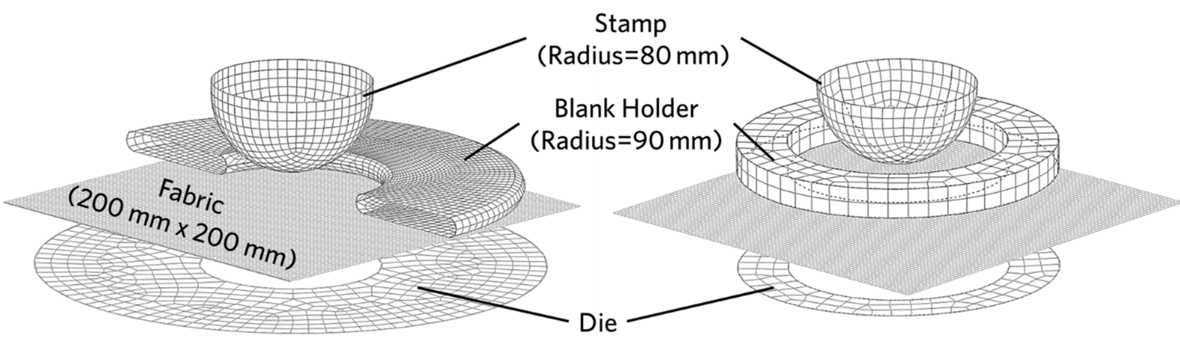

Figure 2. Arrangement of the finite element model for full round (even) and half round (uneven) blank holding conditions.

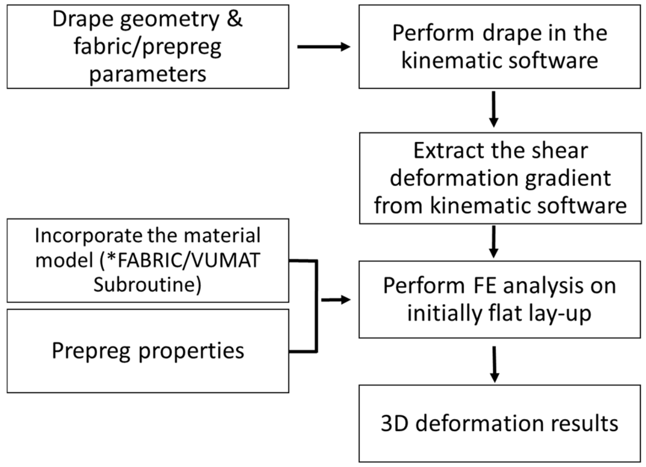

Figure 3. Overview of the hybrid kinematic (HYKE-1) model.

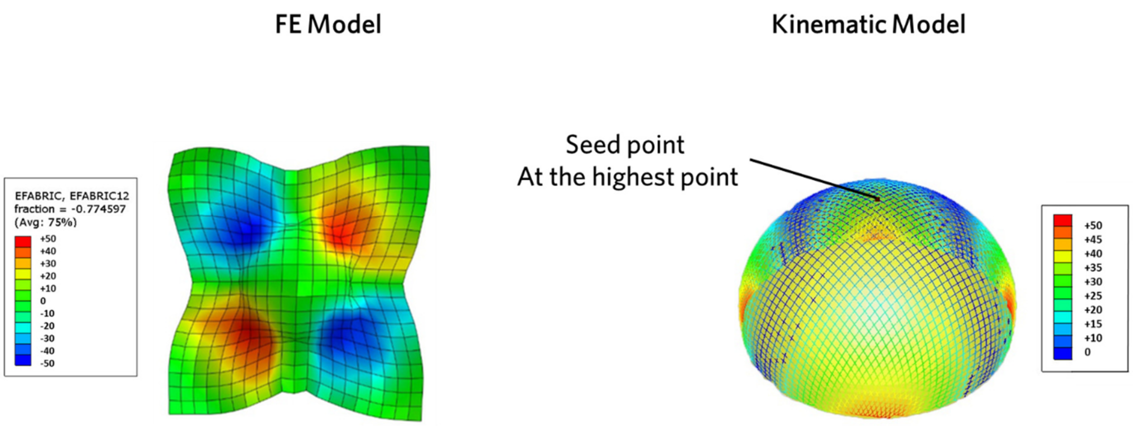

Figure 4. Comparison between the FE-based model and kinematic model for the even pressure case (i.e. using full round blank holder).

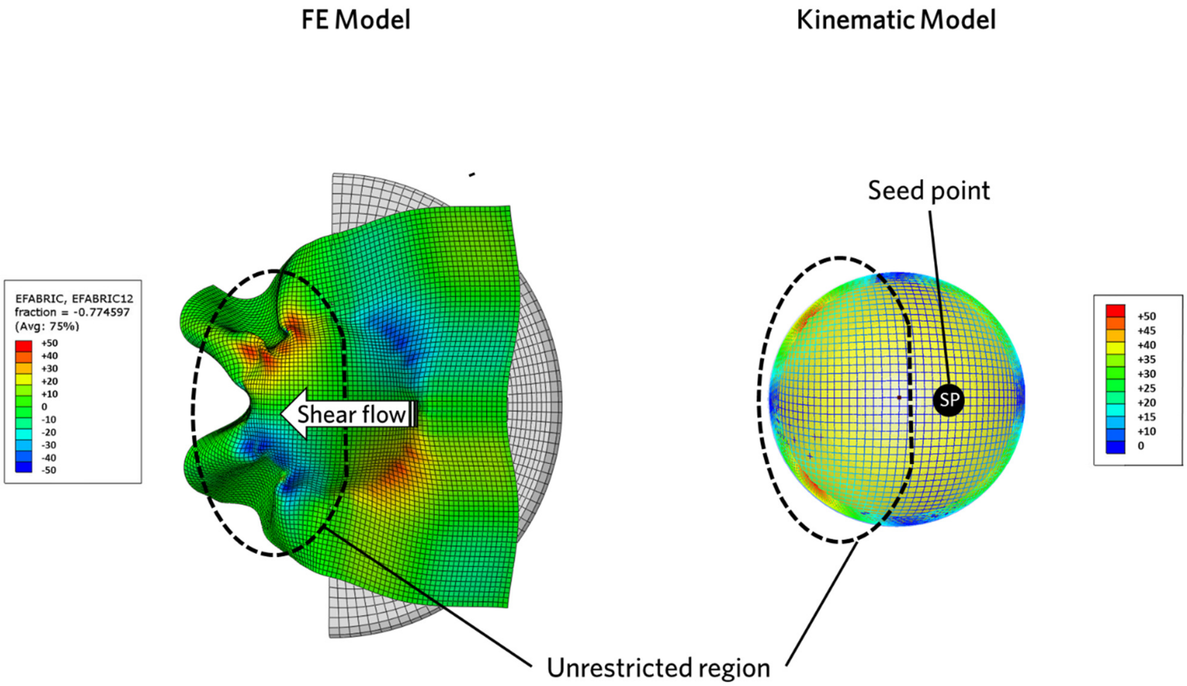

Figure 5. Comparison between the FE-based model and kinematic model for the uneven pressure case (i.e. using half round blank holder).

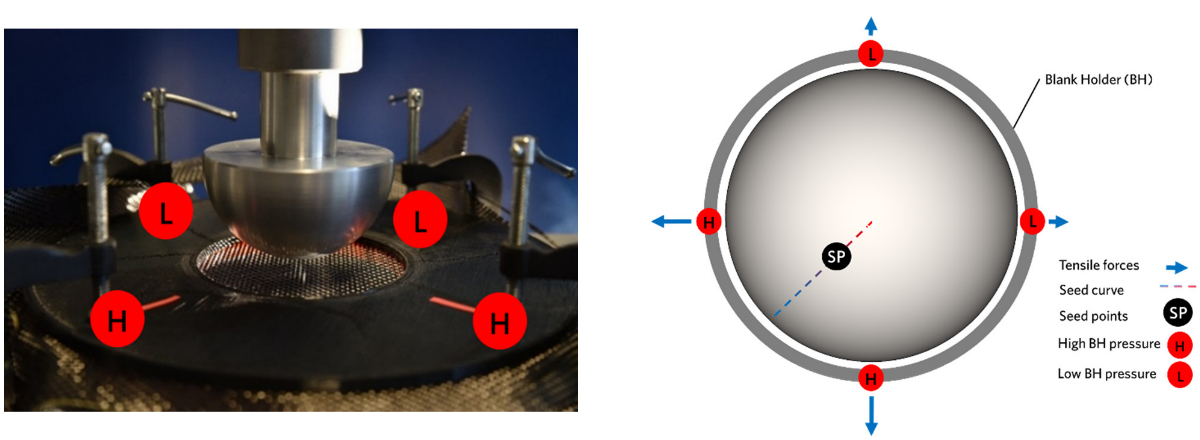

Figure 6. Experimental setup and schematics of boundary condition/pressure distribution in an asymmetric forming trail with discrete blank holders.

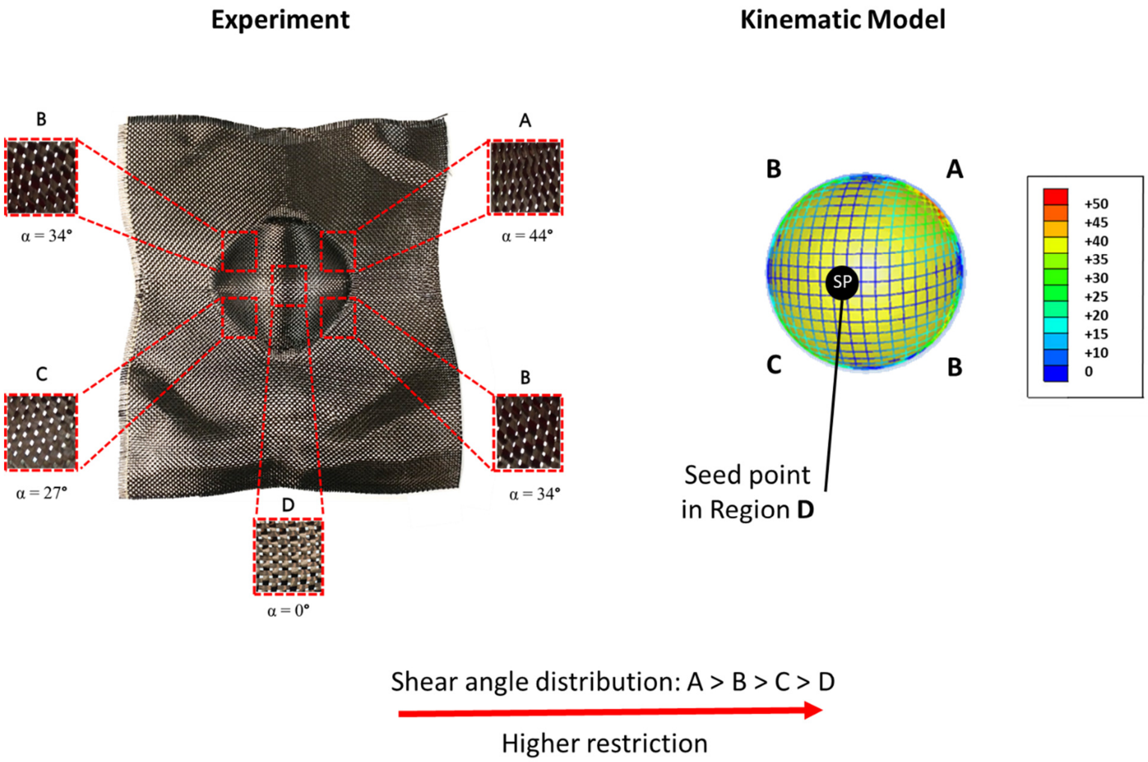

Figure 7. The plain fabric formed onto hemisphere under an asymmetric boundary condition per figure 6. The shear angles are zoomed-in for better visual inspection (left); The kinematic model used the effective seed point approach (right). α refers to the shear angle of the fabric. The difference between the predicted angles and actual angles was less than 5%.

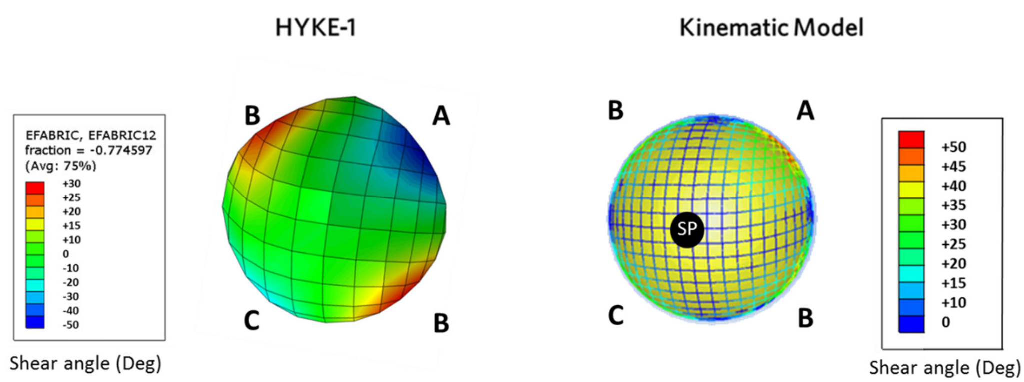

Figure 8. Comparison between the solution obtained using the HYKE-1 model (left) and the kinematic model (right) for the unsymmetrical blank holder condition shown in figures 6 and 7. The difference between the predicted angles by the two models was less than 2%.