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# A parametric sensitivity study on preforming simulations of woven composites using a hypoelastic computational model

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**Abstract**

Preforming simulation for structural composite processing can significantly assist in the development of forming tools, prediction of manufacturing issues, optimization of process parameters and structural design analysis. The present study is aimed at investigating the influence of some important parameters in composite forming using a hypoelastic computational model developed for simulating the deformation behaviour of fibrous materials. The process parameters considered within this numerical work investigate the effects of binder force, coefficient of friction and forming speed. The study is conducted using two most commonly used double-curvature geometries for analysis of woven composites: double dome and hemisphere. It has been shown with this comprehensive study that the forming simulations are greatly affected by the choice of process parameters, and models based on finite element approach, such as the proposed hypoelastic model, can only predict its effects.

**Keywords**

Preforming simulation, sensitivity study, hypoelastic model, hemisphere, double dome

## Introduction

Textile composites have emerged with their increasing utilization in the high performance domains such as aeronautics, automotive, defense and sports. Such materials offer some key properties to be used in shell structures having complex contours. The privileged draping behaviour of the woven composites usually makes them a priority candidate for structural parts having double-curvature shapes. The drapeability of a fabric linked to its intraply shear behaviour largely depends upon the woven architecture.[1] A complex shape of the preform (dry or prepreg) can be obtained by a punch and die-forming process from initially flat and undeformed textile reinforcement. This yields re-orientation of fibres and affects the permeability of the continuous reinforcement considered important for the resin injection stage.[2,3] Moreover, the information generated with the preforming stage is very useful in the design phase of parts and tooling required to make the parts.

Composite process simulations indeed hold considerable significance to reduce the time and cost associated with the product and process development cycle of new composite structural parts.[4,5] Particularly, the preforming simulations can effectively contribute in the areas such as the development of forming tools, structural design analysis, prediction of manufacturing issues and optimization of process parameters. Therefore, the numerical analysis of a composite forming process is important in order to determine the optimal conditions for successful development of forming operation of a preform with minimum defects. The optimal selection of process parameters such as blank holder or binder force, forming

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speed and tool-ply interactions can contribute to afford a good quality forming of woven composites.[6,7]

The forming analysis of textile composite reinforcement essentially performed in practice can be categorized into three different scales.[8] The scales of reinforcement depend over the nature of its structural formation and classified in order of smallest element to global part. All of them are defined in order to probe the mechanical behaviour of the textile reinforcement during deformation. These scales are termed as micro-, meso- and macro-scales. The micro-scale is the study of reinforcement at fibre level whereas meso-scale deals the reinforcement at unit-cell level. The macro-scale considers the reinforcement at large scale composed of few unit cells to a component or product level. Macro-scale studies determine the global behaviour of the fabric or reinforcement during deformation. The present study is particularly focused towards obtaining response of a fabric at macro-scale level. Macro-scale models consider a simple equivalent media, i.e. a homogeneous media or a set of elements. The analysis of composite forming process comes under the category of macro-scale modelling of textile drape behaviour. The models developed for macro-scale are typically implemented in a non-linear finite element program to perform forming simulations.[9,10]

In the above context, two different approaches are being used for preforming simulation of woven fabrics: the geometrical approach and the mechanical approach. The geometrical approach is based on the kinematic models[11,12] and considers the yarns to be pinned together at the crossover points of the weave. The yarns are inextensible and free to rotate around the pin-joints. Such models are able to measure the change in the angle between the warp and weft yarns of the fabric during deformation conforming to contours of the model or part. This method is fast and fairly efficient; however, such models do not account for the mechanical behaviour of the woven reinforcement such as the non-symmetric shear behaviour of the non-crimp fabrics. Moreover, the kinematic models are unable to take into account the loads imposed during forming such as tool–fabric interactions and binder force effects. Hence, the limitations with the kinematic approach do not allow the user to conduct parametric studies of composite processing.

The mechanical approach involves finite element models to be used for forming analysis of aligned fibre-reinforced materials. The discrete and the continuous models fall in the category of mechanical approach. The discrete models[13,14] of fabrics are based on modelling the woven yarns usually described by simplified elements such as trusses or beams connected by tensional or rotational springs. The difficulty in accounting for the complex behaviour of woven cells, the large number of components and the contacts with friction make this approach expensive from the computation point of view. Therefore, a balance must be established between the precise description and the simplicity of the model used for local components.

The continuous approach[15–18] considers the fibrous material as a continuum. The textile reinforcement indeed is not continuous at lower scales but it can be considered as continuous on average at macroscopic scale. The benefit of this approach lies in the exploitation of finite element codes using standard elements. The approach used in the present work is based on a continuous approach using hypoelastic behaviour of fibrous reinforcement.[9,17] The objective derivative used here considers bi-directional material, i.e. warp and weft, for analysis of a fabric at macroscopic level. The two directions of fibres can undergo excessive re-orientation and determination of shear-angle distribution over the draped part is very important. It helps to determine the wrinkling, thickness variation, bridging effects and changes in the permeability of the material in the case of dry reinforcement. Therefore, the numerical model selected should be able to predict such changes of relative deformation and displacement between warp and weft yarns.

The scope of the present study is to conduct numerical investigations related to the effects of process parameters on the draping of woven fabrics. Two double-curvature geometries have been used for the preforming simulations: benchmark geometry of double dome designated for analysis of woven composites and a classical model of hemispherical dome. The process parameters indeed play a very important role to optimally conclude the forming of woven composite reinforcements. Blank holder force, forming speed and coefficient of friction between fabric and tools are some key parameters that affect the formability of aligned fibre-reinforced materials. In order to predetermine correctly the parameters of forming speed and binder force, numerical studies can offer great advantages in terms of time and cost. Therefore, the computational models should have the capacity to respond convincingly towards predicting numerical changes of such process parameters. It will be shown here that the hypoelastic computational model, implemented in a commercial finite element code of Abaqus through user material subroutine of VUMAT, can predict effectively the mechanical behaviour of woven materials during deformation. The parametric sensitivity study conducted numerically using the developed model has produced interesting results. Such comprehensive parametric studies of sensitivity analyses are possible by adopting the mechanical approach in modelling the draping of fabrics. Here, the hypoelastic computational model has been described briefly followed by the sensitivity studies.

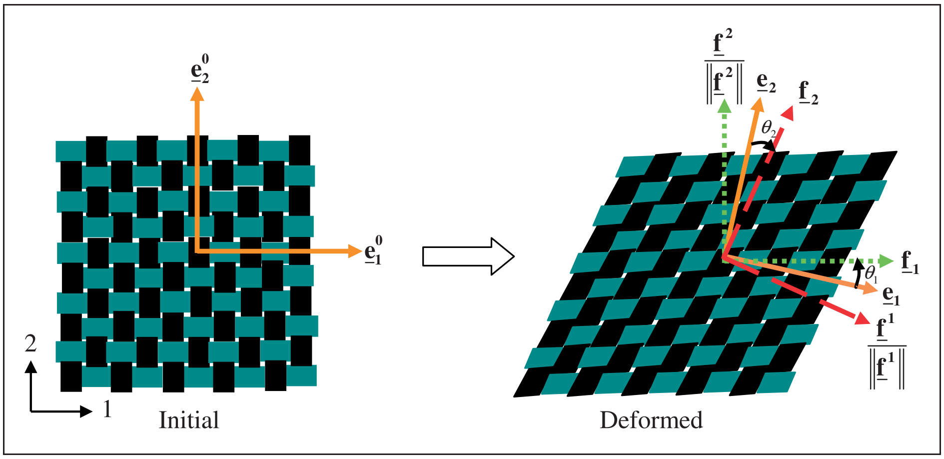

**Figure 1.** Orientation of GN axes $\underline{e}_\alpha$ and fibres axes $\underline{f}_\alpha$ before and after deformation during a simple shear test. Initially, both frames are superimposed: $\underline{f}_\alpha^{\mathbf{0}}=\underline{e}_\alpha^{\mathbf{0}}$ where $\alpha = 1, 2$.

## Hypoelastic computational model for woven composites

Keeping in view to the geometrical architecture and specific deformation modes of the textile reinforcements, the selected constitutive model should satisfy the theory of large transformations. The modelling phenomena include both material and geometric non-linearities due to large displacements and deformations of the yarns. It is indeed a judicious choice of this study to adopt hypoelasticity, which can meet these requirements while remaining close to the physical problem.

Generally, the hypoelastic laws, written as rate constitutive equations in finite element codes,[19,20] are of the following form

$$\underline{\underline{\sigma}}^{\nabla} = \underline{\underline{\underline{\underline{C}}}}:\underline{\underline{D}} \tag{1}$$

where $\underline{\underline{\sigma}}$ and $\underline{\underline{D}}$ are the Eulerian tensors of Cauchy stress and the strain rate, respectively. $\underline{\underline{\underline{\underline{C}}}}$ is a Eulerian constitutive tensor orientated by a unit vector in the material directions. $\underline{\underline{\sigma}}^{\nabla}$ is an objective derivative of $\underline{\underline{\sigma}}$ defined to avoid stress change due to rigid body rotations in $\dot{\underline{\underline{\sigma}}} = \mathrm{d}\underline{\underline{\sigma}}/dt$.

The approach used in this study, in case of fibrous materials, exploits an objective derivative based on the fibre rotation tensor $\underline{\underline{\Delta}}$. The objective derivative of the Cauchy stress tensor with respect to fibre rotation tensor is

$$\underline{\underline{\sigma}}^{\nabla} = \underline{\underline{\Delta}}.\left(\frac{\mathrm{d}}{\mathrm{dt}}\left(\underline{\underline{\Delta}}^T.\underline{\underline{\sigma}}.\underline{\underline{\Delta}}\right)\right).\underline{\underline{\Delta}}^T \tag{2}$$

whereas $\underline{\underline{\Delta}}$ is the rotation from the initial frame to the frame of fibre. In case of bidirectional material data, it is based on each of warp and weft direction of fibres. It has been shown subsequently that the fibre rotation tensor takes the form $\underline{\underline{\Delta}} = \underline{f}_1 \otimes \mathbf{e}_1 + \underline{f}_2 \otimes \underline{e}_2$ using two fibre directions, where $\underline{f}_1$ and $\underline{f}_2$ are the current fibre directions and $\underline{e}_1$ and $\underline{e}_2$ are the current orientations of Green-Naghdi (GN) axes – the default work basis of Abaqus/Explicit.

The computation of stress in the fibrous materials has been illustrated using the orientations of fibre axes and GN axes in the initial and deformed states as shown in Figure 1. The GN axes $\underline{e}_\alpha$ in the current configuration (the average rotation of the material axes) are updated using orthogonal rotation matrix $\underline{\underline{R}}(\underline{\underline{R}} = \underline{\underline{F}}\underline{\underline{U}}^{-1})$ and the initial orientation of GN axes $\underline{e}_\alpha^{\mathbf{0}}$ as

$$\underline{e}_\alpha = \underline{\underline{R}}.\underline{e}_\alpha^{\mathbf{0}} \tag{3}$$

The index '$\alpha$' takes the values of 1 and 2 and represents the warp and weft direction of fibres. The axis-3 is common for both GN and fibre frames, and it is perpendicular to the planes 1–2.

The current fibre directions $\underline{f}_\alpha$ are obtained using the deformation gradient tensor $\underline{\underline{F}}$ and the initial orientation of fibres $\underline{f}_\alpha^{\mathbf{0}}$

$$\underline{f}_\alpha = \frac{\underline{\underline{F}}.\underline{f}_\alpha^{\mathbf{0}}}{\left\|\underline{\underline{F}}.\underline{f}_\alpha^{\mathbf{0}}\right\|} = \frac{\underline{\underline{F}}.\underline{e}_\alpha^{\mathbf{0}}}{\left\|\underline{\underline{F}}.\underline{e}_\alpha^{\mathbf{0}}\right\|} \tag{4}$$

where $\underline{f}_\alpha^{\mathbf{0}}$ and $\underline{e}_\alpha^{\mathbf{0}}$ are assumed to coincide initially. After the update of the current GN axes and fibre axes, the strain components from the code work basis (GN basis) are transformed to the fibre bases using a transformation matrix $[\mathrm{T}_1]$ constructed between the two frames, i.e. between $e\left(\underline{e}_1, \underline{e}_2\right)$ (stands for GN frame) and

$f_1(\underline{\mathbf{f}}_1, \underline{\mathbf{f}}^2/\|\underline{\mathbf{f}}^2\|)$ (an orthogonal frame having first fibre direction $\underline{\mathbf{f}}_1$). Similarly, the transformation matrix $[\mathbf{T}_2]$ is based on the change in angle between the GN frame and the second orthogonal frame $f_2(\underline{\mathbf{f}}^1/\|\underline{\mathbf{f}}^1\|, \underline{\mathbf{f}}_2)$ having second fibre direction $\underline{\mathbf{f}}_2$.

The strain increments $[d\boldsymbol{\varepsilon}]_e$ available in the GN frame are transformed to the fibre strain increments expressed in the first orthogonal frame as

$$[d\boldsymbol{\varepsilon}]_{f_1} = [\mathbf{T}_1]^T [d\boldsymbol{\varepsilon}]_e [\mathbf{T}_1] \tag{5}$$

The strain increments expressed in the second orthogonal frame having the updated second fibre directions are computed as

$$[d\boldsymbol{\varepsilon}]_{f_2} = [\mathbf{T}_2]^T [d\boldsymbol{\varepsilon}]_e [\mathbf{T}_2] \tag{6}$$

The in-plane shear-strain increment $d\gamma$ is defined to be the change in the angle (radians) between the warp and weft yarns, and specifically here, it is equal to the sum of the components of shear-strain increments calculated from equations (5) and (6), i.e.

$$d\gamma = \mathrm{d}\varepsilon_{12}^{f_1} + \mathrm{d}\varepsilon_{12}^{f_2} \tag{7}$$

The stress increments along fibre directions are computed using the constitutive matrix in the fibre direction $[\mathbf{C}]_f$ in conjunction with equations (5) and (6) (for details, consult[17])

$$[d\boldsymbol{\sigma}]_{f_1} = [\mathbf{C}]_{f_1} [d\boldsymbol{\varepsilon}]_{f_1} \tag{8}$$

and

$$[d\boldsymbol{\sigma}]_{f_2} = [\mathbf{C}]_{f_2} [d\boldsymbol{\varepsilon}]_{f_2} \tag{9}$$

The stress increments computed in equations (8) and (9) are accumulated in each fibre frame consistent with the objective derivative in equation (2) and employs the mid-point integration scheme to compute stress state at time step $t^{n+1}$ knowing at $t^n$,[21]

$$\left[\boldsymbol{\sigma}^{n+1}\right]_{f_1^{n+1}} = [\boldsymbol{\sigma}^n]_{f_1^n} + [\mathrm{d}\boldsymbol{\sigma}]_{f_1^{n+1/2}} \tag{10}$$

$$\left[\boldsymbol{\sigma}^{n+1}\right]_{f_2^{n+1}} = [\boldsymbol{\sigma}^n]_{f_2^n} + [\mathrm{d}\boldsymbol{\sigma}]_{f_2^{n+1/2}} \tag{11}$$

Finally, the stresses computed in the two fibre frames using equations (10) and (11) are then transformed to the GN frame as

$$[\boldsymbol{\sigma}]_e = [\mathbf{T}_1][\boldsymbol{\sigma}]_{f_1}[\mathbf{T}_1]^T + [\mathbf{T}_2][\boldsymbol{\sigma}]_{f_2}[\mathbf{T}_2]^T \tag{12}$$

Thus, the stress tensor in the code work basis (GN frame) is the sum of the transformed stresses calculated in the two orthogonal frames.

The working code is Abaqus/Explicit, and the formulations developed for stress computation algorithm are written in FORTRAN code and implemented through a user material subroutine VUMAT. The working of the algorithm occurs in the form of a loop.

## Woven composite preforming tests

The forming models used to conduct forming simulations are the most commonly studied geometries for composite forming simulations[6,7,9,16–18] i.e. a hemispherical dome (HD) and a double-dome benchmark designated originally for analysis of woven composites. Both forming models consist of die, punch and blankholder considered as rigid forming tools and a deformable blank or test specimen placed in between the die and the binder. The blankholder designs used are segmented for both the cases of double dome and hemisphere. The advantage lies in the control of blankholder segments independently that can help to predict the influence of unbalanced binder forces during a single forming operation. All three forming tools are modelled as discrete rigid bodies and meshed with 3-D triangular rigid elements (R3D3) with a mesh size of 3 mm. The elements used for numerical analysis of deformable blank are M3D4R: 3D quadrilateral membrane elements with reduced integration. The approximate element edge length is 3 mm.

The orientations of the fibres are taken along the edges of the quadrilateral elements. The same is true for the ±45° fibre orientations where the elements are meshed at 45°, with respect to the blank sides, so that fibres follow the edges of the elements. The aligning of mesh with initial fibre directions is one of the solutions to avoid intra-ply shear locking.[18]

The material characteristics and process parameters mostly used for numerical forming simulations carried out in this study are detailed in Khan et al.[9,17] and are mentioned as below:

- First, elastic tensile modulus (warp direction), $E_1 = 35{,}400$ MPa
- Second, elastic tensile modulus (weft directions), $E_2 = 35{,}400$ MPa
- Mass density, $\rho = 0.00253$ g/mm$^3$
- Blank holder force = 100 N
- Punch velocity = 100 mm/s
- Coefficient of friction (Tool/Ply) = 0.2 (double dome)
- Coefficient of friction (Tool/Ply) = 0.25 (hemisphere dome)

The in-plane shear rigidity $G_{12}$ of the commingled glass/polypropylene BPW fabric has been deduced as a function of shear angle '$\gamma$' in radians

$$G_{12}(\gamma) = 8.48|\gamma|^4 - 12.0972|\gamma|^3 + 6.1275|\gamma|^2 - 0.83|\gamma| + 0.051 \quad (13)$$

The schematic representation of the geometry of HD and its FEA model setup is shown in Figure 2. Figure 3 represents the deformed shape of the preform obtained from forming simulation of hemispherical model. The simulation results are compared with experiment using material properties described in the recent research work of the first author.[28] This is a carbon/epoxy prepreg material that has been preformed at room temperature, and the deformed white grid-lines show the extent of shear in the prepreg ply. The grid-lines were drawn parallel to the tows of the carbon fabric reinforcement in the undeformed state. For more details on the simulation and experimental results, it is suggested to consult a recent contribution from the author.[28]

Figure 4 shows the deformed state of the double-dome forming models. The forming simulations for ±45° fabric tows in the reference configurations (Figure 4) compared with experiment show that the model selected can fairly predict the specific deformation behaviour of fibrous materials.

Figure 5 shows the experimental and simulation results for the double-dome preforming the edge profile obtained over quarter of the benchmark geometry. Alternatively, it can also be regarded as the material draw-in obtained along edges of double-dome quarter model. The results of material draw-in for the deformed configuration shown in Figure 5 are in good agreement. More details related to validation of the double-dome forming model can be found in the author's contributions.[9,17]

## Parametric sensitivity study: Results and discussion

The preforming of textile composites is indeed a critical stage for successful forming of parts in the case of RTM and compression-moulding processes. Keeping in view to the importance of this forming stage, a comprehensive process parametric sensitivity study has been conducted, which will demonstrate the capability of the

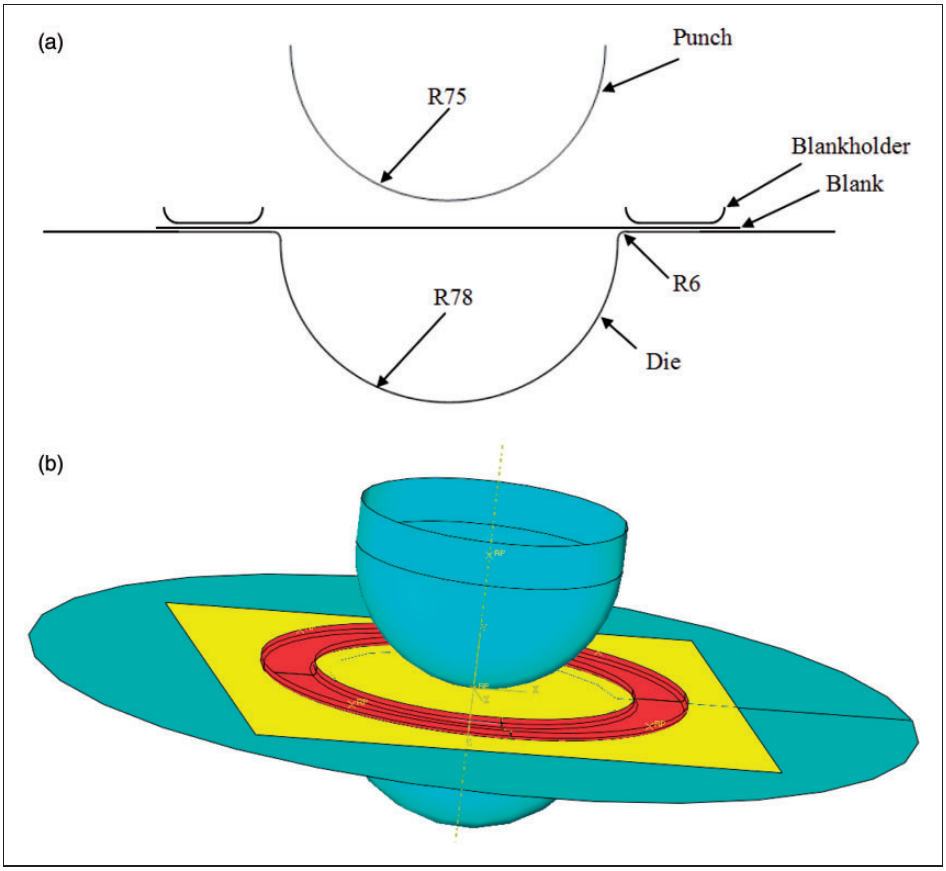

**Figure 2.** Schematic representation of HD: (a) 2D model geometry and; (b) 3D model setup for preforming simulations. HD: hemispherical dome.

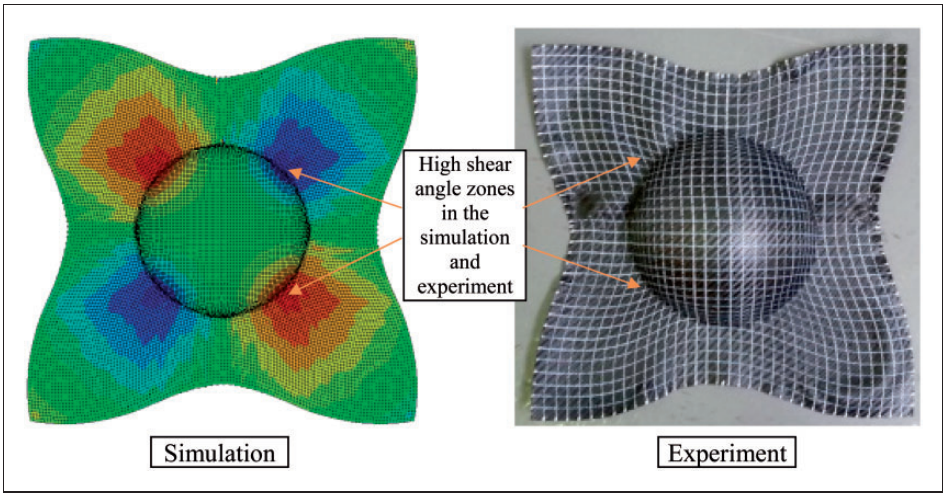

**Figure 3.** The preforming simulation and experiment achieved with hemispherical dome forming device with 0°/90° initial orientation of tows.

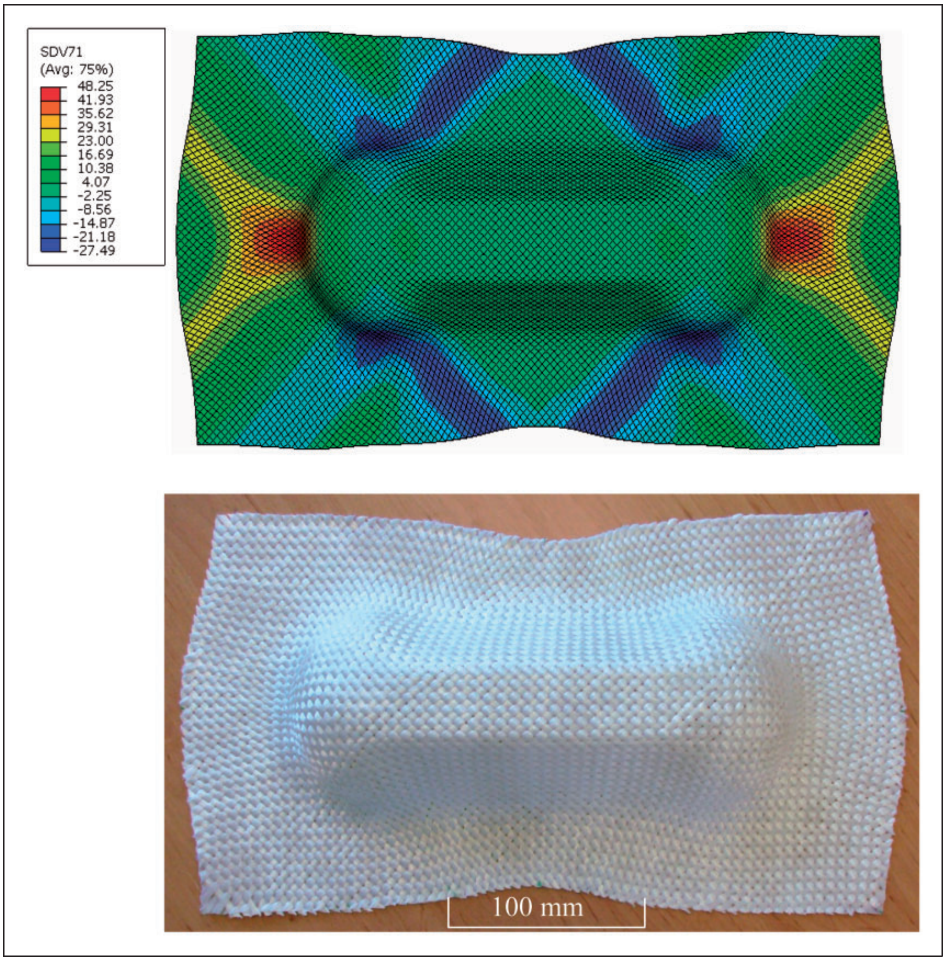

**Figure 4.** Preforming of double dome achieved with numerical simulation and experiment of a fabric with ±45° tows in the undeformed configuration. SDV71 (for all cases) is the shear angle in degrees.

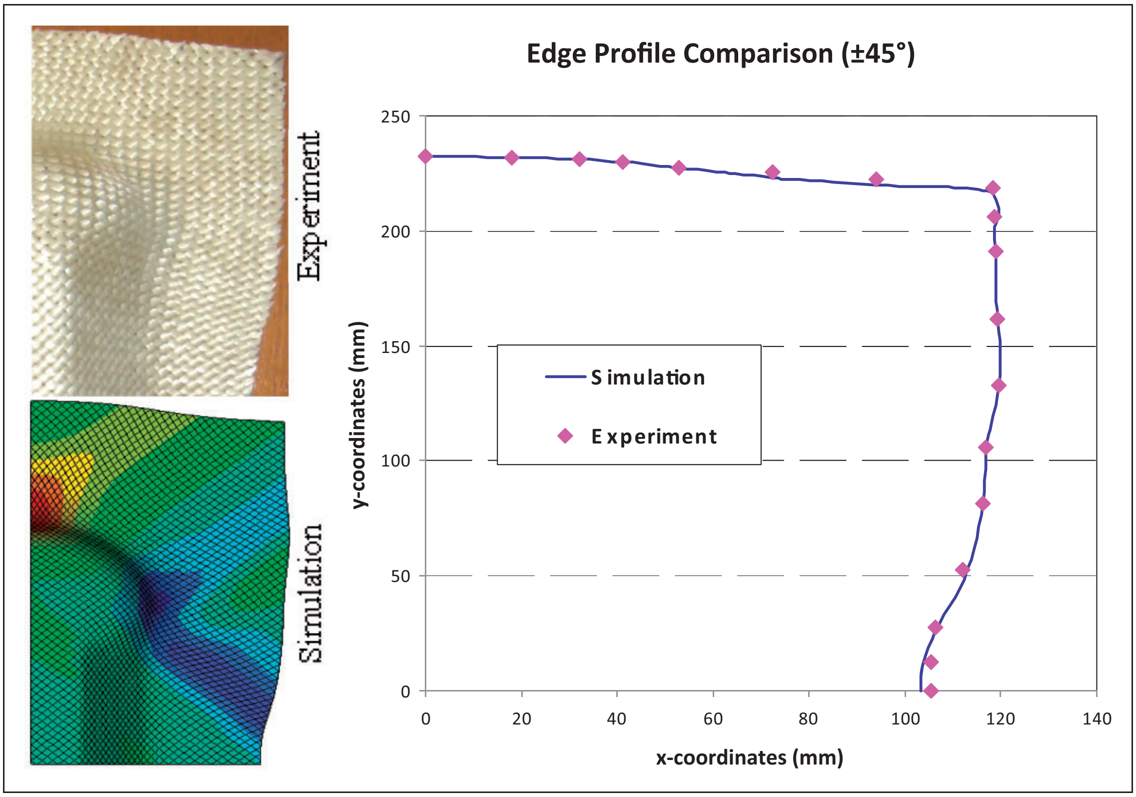

**Figure 5.** Edge profile comparison of quarter of double-dome benchmark tests with ±45° fibre orientations in the reference configurations.

developed numerical model as well as help us understand the influence of some key process parameters for composite forming. The parameters investigated are blankholder or binder force, punch velocity or forming speed and tool-ply friction. The influence of these parameters is studied separately for an appropriate range of values. The results are compared considering the final shape and reorientation of the fibres in the draped part. It has been observed that the results are quite sensitive with the variation of process parameters. Moreover, each process parameter has been studied using both models of hemisphere and double dome.

## Binder force

The role of binder or blank holder in the forming processes of composite materials is possibly the most important, and it has also been highlighted to some extent in the past.[6,22,23] A blankholder is very essential in order to obtain a preform with little defects: with no or minimum possible wrinkling. The magnitude and distribution of binder force determine correct execution of the preforming stage and affect the evolution of shear angle over draped part. Binder force creates in-plane tension in the fabric during deformation and helps a smooth flow of the composite ply during forming operation. This is sometimes referred as pre-tension in the fabric. The pre-tension affects the deformation behaviour of fabric and depends on the binder force distribution and its magnitude. Moreover, compressive and tensile strains tend to increase by increasing the magnitude of binder force. Compressive strains usually develop during scissoring or shearing of the fabric during deformation. This is also meant to be the lateral compression of the yarns. Lateral compression of the yarns is an important deformation mode of the fabric, which determines the initiation of wrinkling of the fabric reinforcement. Therefore, by manipulating the binder force, an optimized draping of the reinforcement can be achieved.

In order to clearly observe the effect of blankholder force on the draped part, a high ratio of unbalanced force or pressure has be deliberately applied at the two diagonals of the blank for the both forming cases of hemisphere and double dome. Since the two forming models have split blankholders, it helps to apply the binder forces individually. It has been observed that such unbalanced forces severely affect the material draw-in along the boundary edges of the preform. Also, the shear-angle distribution has shown a great variation in the draped part (see Figure 6).

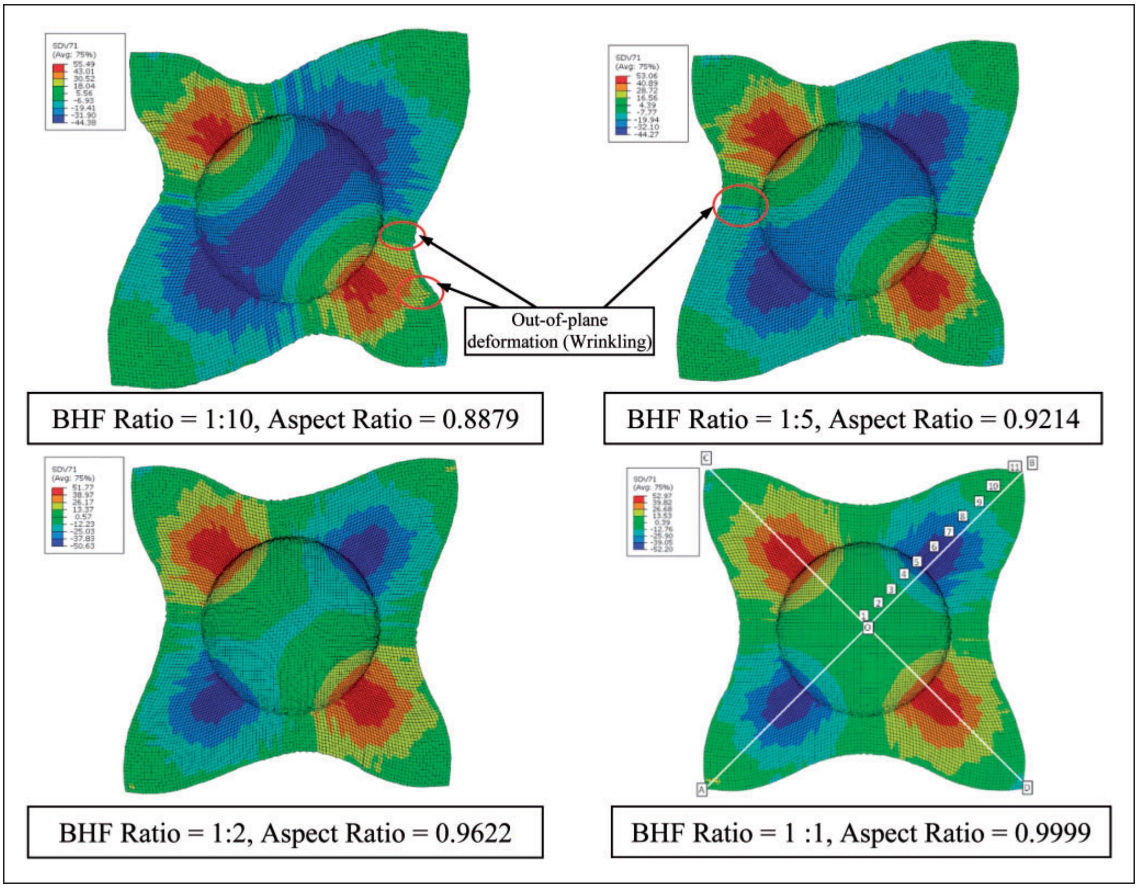

**Figure 6.** The evolution of shape and shear angle shear angle (degrees) and distribution in the hemisphere model with different unbalanced BHF ratios. BHF: blank holder force.

The two opposite diagonal corners have emerged with the same shape and almost the same shear-angle contour. This is due to the fact that they have experienced the same binder force during the test. The binder force ratios used for simulations with HD are used as 1:10, 1:5, 1:2 and 1:1 (balanced). It can be observed from Figure 6 that material draws-in more in the quarters of model where small blankholder forces are applied. Moreover, some out-of-plane deformations or wrinkling can be observed at those corners. There is also a high variation of shear angle i.e. up to 10° along the two diagonals. The aspect ratio mentioned in Figure 6 is obtained as the ratio of two diagonals i.e. CD/AB after deformation.

Another important form of simulation results related to the material draw-in or edge profile comparison is presented in Figure 7. The results are shown for three different magnitudes of balanced forces on the symmetrical quarter model of hemisphere. A relative variation in the edge profile of up to 4 mm has been observed for the three cases at different regions along the edges of the preform.

Figure 8(a) shows the image of an experimental forming test achieved on a 2 × 2 twill weave of thermoplastic with a non-uniform and unbalanced force.[7] These effects of blankholder force[7] can be compared to simulation results shown in Figure 6, and it can be concluded that the blankholder force has a significant role on the formability results of a composite ply as well as these effects are possible to predict using finite element based preforming simulations.

It can also be concluded that blankholder force has a direct impact on the shear behaviour of the material, which creates non-symmetric shape and shear of the part during forming. The evidence to the above fact can be observed from the deformed grid in Figure 8(a) and also in Figure 8(b) where the blankholder force is uniform; however, the inherent material shear behaviour is non-symmetric because of the stitching directions. The stitch tensile and cross directions retain different level in-plane shear rigidity in the two orthogonal directions but the effects on the drapeability of the material are similar to the ones obtained with unbalanced blankholder forces.

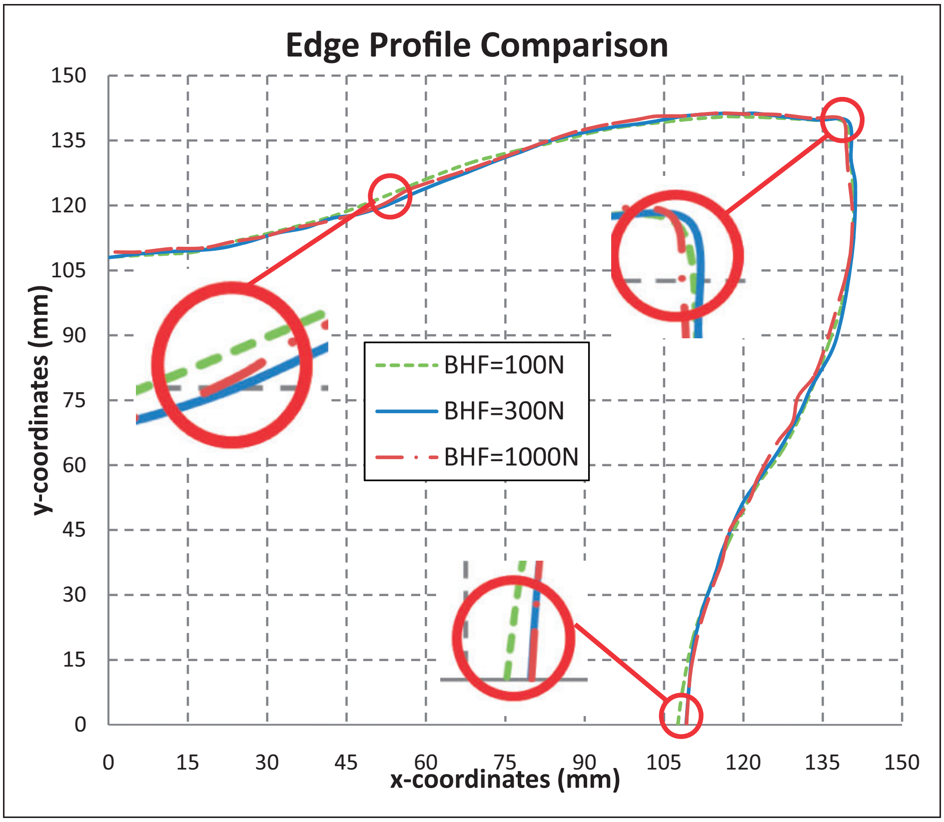

**Figure 7.** The edge profile comparison for the balanced BHF ratio = 1:1 in the hemisphere model with different unbalanced BHF ratios for a 0°/90° orientation of fibres in the undeformed configuration. BHF: blank holder force.

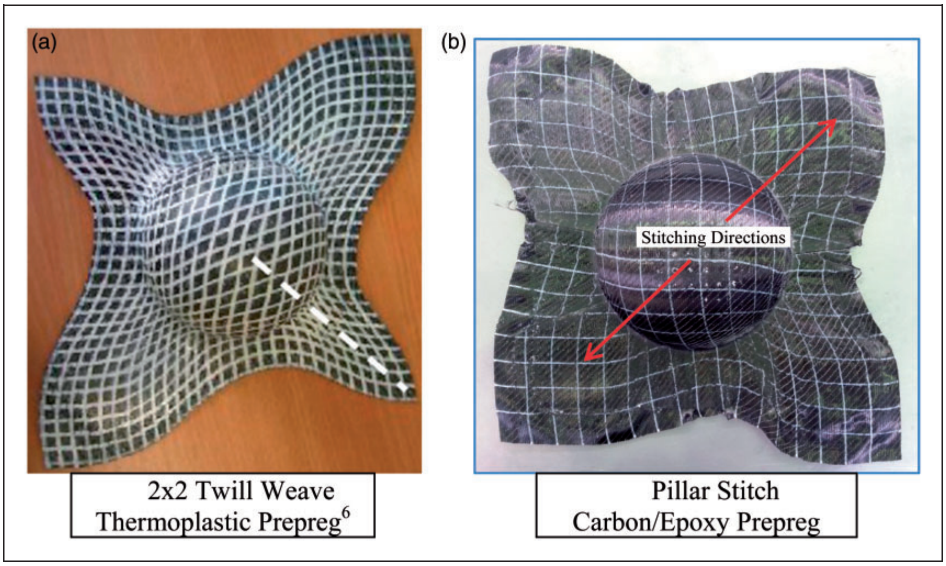

**Figure 8.** Experimental observations on the effects of non-uniform BHF (a)[7] and related effects generated by non-symmetric in-plane shear property with Non-Crimp Fabric (NCF) prepreg preforming (b). BHF: blank holder force.

The effect of non-uniform binder force has also been studied with the double-dome preforming simulations. Figure 9 shows the simulation results achieved with two binder pressures i.e. of 0.3 MPa and 0.03 MPa applied over the segmented blankholder. It can be observed that the shear-angle evolution has been largely affected by the unbalanced pressure i.e. up to a variation of 20°. The material draw-in has also been affected but it was

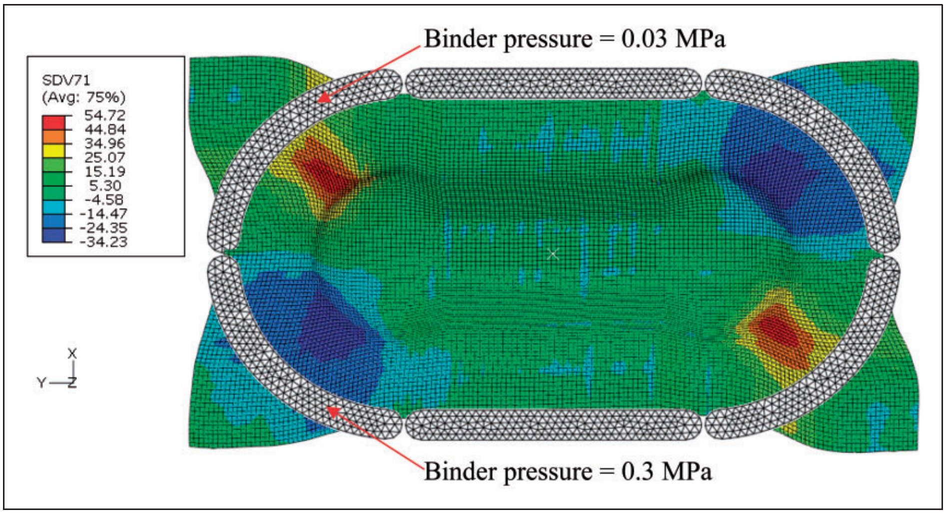

**Figure 9.** The shear angle (degrees) evolution and distribution in the full double-dome model with unbalanced binder pressure for a 0°/90° orientation of fibres in the reference configuration.

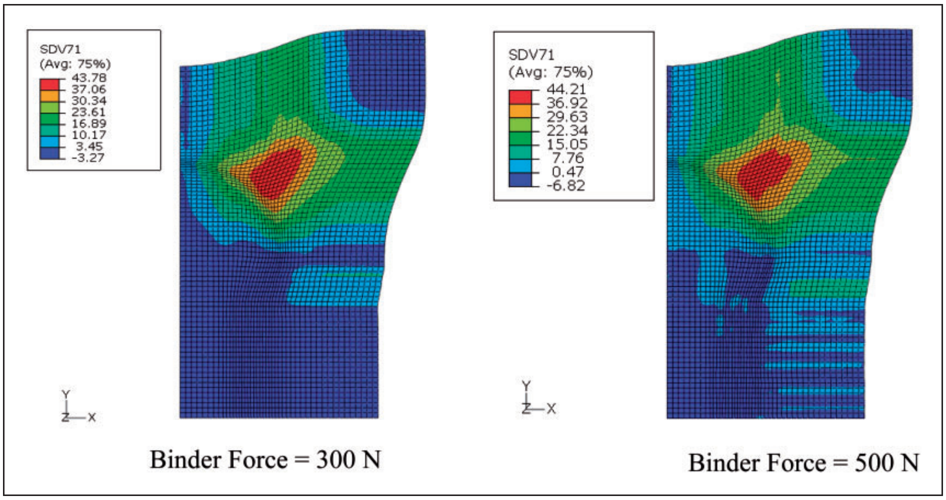

**Figure 10.** The shear angle (degrees) evolution in quarter symmetrical model of double dome with two cases of binder force as 300 N and 500 N.

more pronounced in the case of hemisphere. It could be the effect of magnitude of the force that was more for the hemisphere preforming simulations.

Since the opposite diagonal corners have the same binder pressure, they present almost the same magnitude of shear angle and material flow during forming. Consequently, it can be supposed that binder force has serious implications during preforming, and it needs to be optimized for a certain application, i.e. for given geometry of part and type of materials. It has also been observed experimentally that higher than the required level of blankholder forces tear apart the composite plies.

Figure 10 shows the results of shear-angle contour on a quarter of double-dome symmetrical model with two different blankholder forces i.e. 300 and 500 N. These are concentrated forces applied to the binder and therefore distributed uniformly. The results of two simulation cases do not show a significant difference in the predicted shear angles, and this can be attributed to the small difference in binder force used and also being uniform forces over the entire geometry.

### Forming speed

The process parameter of punch velocity determines the forming speed, and it influences significantly the forming results during draping of textile composites observed practically. There are quite few simulation studies that have been conducted to predict the influence of forming

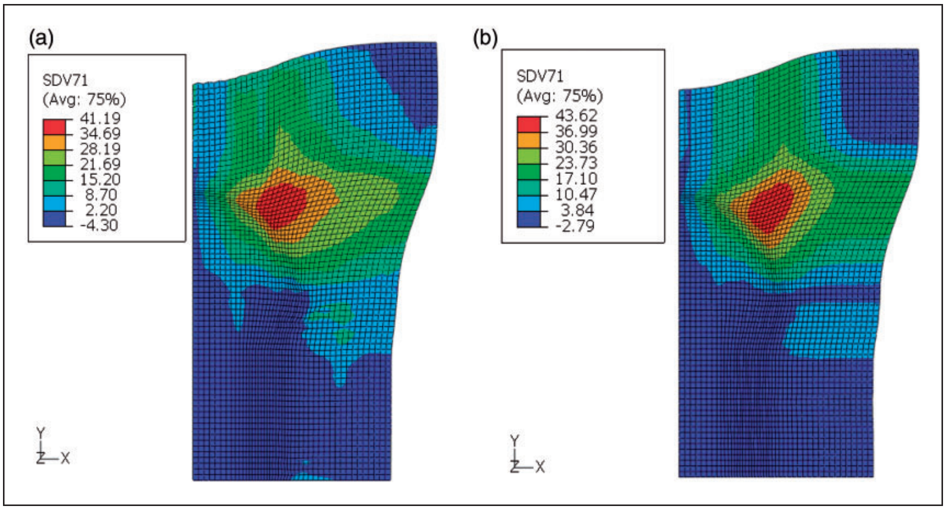

**Figure 11.** Forming results of shear angle in degrees (SDV71) with punch velocities of (a) 50 mm/s and (b) 1000 mm/s.

speed. In Dong et al.,[6] it has been pointed out that forming speeds beyond 100 mm/s have no visible effect on the deformed shape of the fabric whereas the predicted shear angles, measured along a path in the part, have more oscillations at higher speeds. The friction parametric study[24] concludes that increasing the velocity of the punch significantly increases the reaction force on the punch due to the increase in the friction force at all tool/fabric interfaces. It has also been observed that there is always a change in the reaction force on punch yet it was suggested to include a friction model that incorporates the effects of tool/ply slip velocity during thermostamping process simulation for proper design of tools in short production cycle times.

The effect of forming speed has been studied with a variety of punch speeds, e.g. 10, 50, 100 and 1000 mm/s. Figure 11 shows the results of the shear-angle field predicted on quarter of the double-dome model and presents punch velocities of 50 and 1000 mm/sec. The lower punch velocity predicts the shear angle in the final state as 41.19°, which is 2.5° less than high speed forming operation shown in Figure 11. The computation time is largely affected by the change in the punch speed, which indeed is linked to the stable time step computation in an explicit dynamic analysis. Numerically, it is important to use a forming speed with an affordable computation time that gives satisfactory results with reference to the simulation studies carried out with real time used in forming processes. The accelerated numerical simulations with explicit integration scheme are quite efficient and consume reduced CPU time where the forming process is performed at artificially higher draping rates i.e. with high punch velocity. However, this increases artificially the inertia effects and generates high-frequency numerical oscillations on the results such as the reaction forces generated on the punch.

The edge profiles predicted numerically and compared for three different punch velocities i.e. 100, 50 and 10 mm/s are shown in Figure 12. This indicates a relative variation in the amount of material draw-in due to the corresponding change in forming speeds. The maximum relative variation of material draw-in among three different punch velocities is up to 5 mm.

### Tool-ply interactions

In the forming of composites, friction is an important phenomenon that can significantly affect the resulting product geometry. The effect of friction that exists at the interfaces of tool and composite ply is studied here numerically. The tool-ply interactions are introduced in the form of contact property as a function of coefficient of friction used for composite forming analysis. There are number of studies conducted that emphasize the significance of tool-ply friction effects over composite forming results.[6,24–27]

The tool-ply interface friction is introduced in the form of Coulomb friction, and the simulations results shown in 'Woven composite preforming tests', 'Binder force' and 'Forming speed' sections used coefficients of friction as 0.2 for double dome and 0.25 for the HD tests. However, in order to check the sensitivity of this parameter over forming results, a wide range of values were used between 0.1 and 0.4. Here, for example, in Figure 13, the double-dome simulation results with two coefficients of friction i.e. 0.15 and 0.25 are presented. The evolution of positive shear angles is affected by just about 1° but negative shear-angle values differ at maximum by almost 5°, which is considerable in magnitude. Moreover, the distribution of shear angle over draped models shows a large variation.

The comparison of edge profiles for double-dome quarter symmetric model using three different

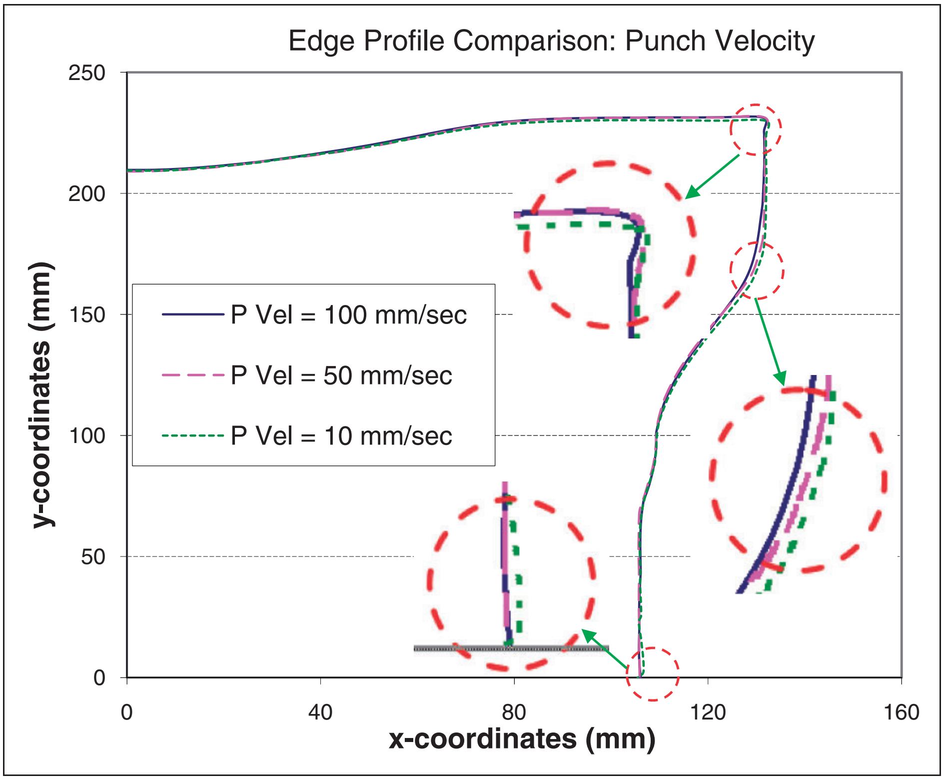

**Figure 12.** Edge profile comparison for three forming cases over quarter of double dome model with 0°/90° initial orientation of fibres predicted with punch velocities (P Vel) of 10 mm/s, 50 mm/s and 100 mm/s.

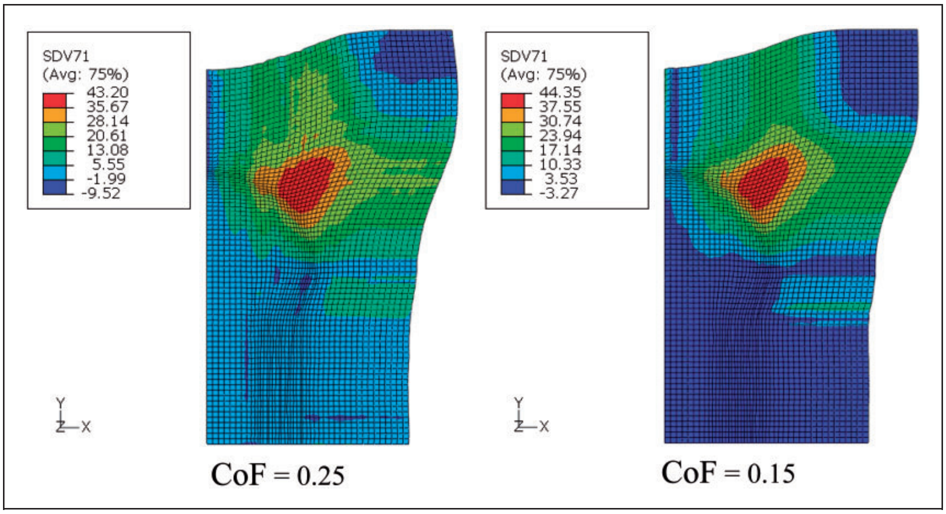

**Figure 13.** The maximum shear angle (degrees) evolution in the two models with two different coefficients of friction (CoF) of 0.25 and 0.15.

coefficients of friction (0.1, 0.15 and 0.2), in the case of ± 45° orientation of yarns in the reference configurations, is shown in Figure 14. The edge profile in the deformed configuration is regarded as material draw-in, and the variations are predicted for different tool-fabric contact properties. The maximum variation in material draw-in among three coefficients of friction is approximately 4 mm at different locations shown in Figure 14.

Another comparison on the prediction of shear angle along the path OB shown in Figure 6 is presented in Figure 15 for the case of HD. The coefficients of

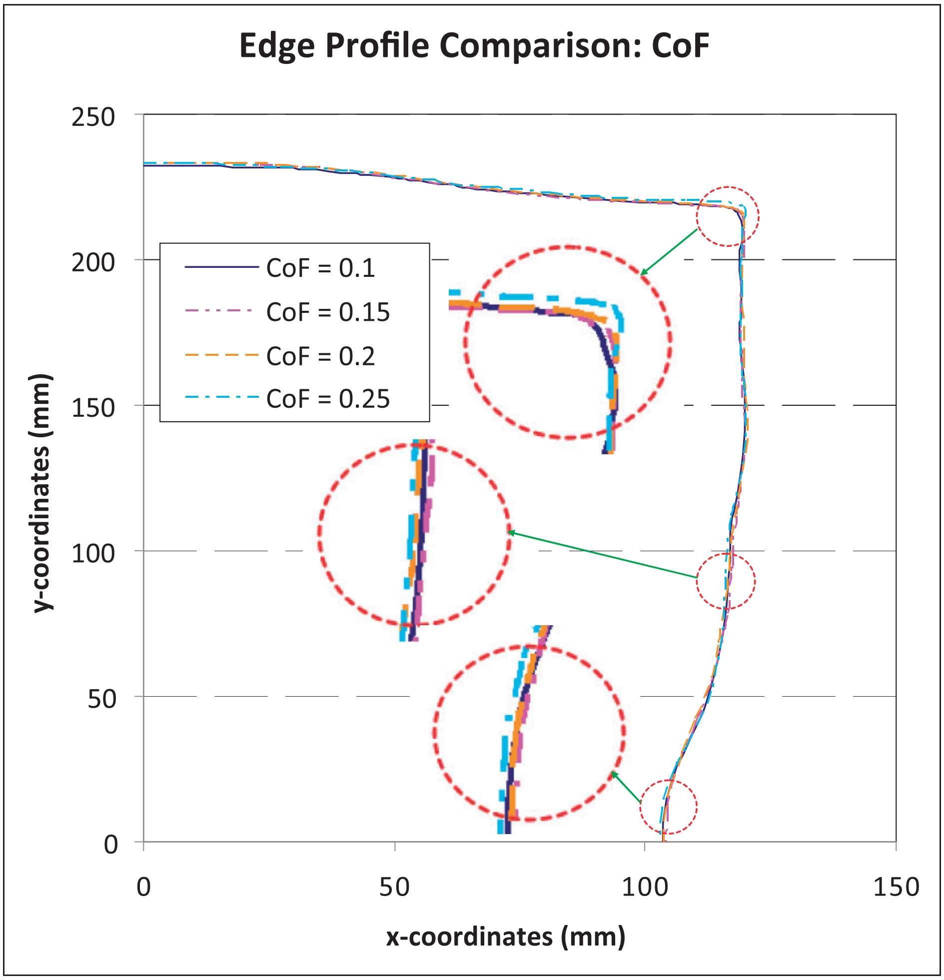

**Figure 14.** Edge profile comparison for four different forming cases over quarter of double-dome model with ± 45° initial orientation of fibres with CoF as 0.1, 0.15, 0.2 and 0.25. CoF: coefficients of friction.

friction used are 0.15, 0.25 and 0.4. There is a difference of about 4° in shear angle in the maximum shear zone at point 6 as indicated in Figure 3 and the maximum difference of about 12° in shear angle at point 11 in the corner. It is worth noting that these differences in shear angles correspond to the maximum and minimum values of the coefficients of friction, i.e. CoF of 0.15 and 0.4. Therefore, the dependency of draping behaviour of the continuous fibrous reinforcement is also linked to the frictional behaviour at the interface of the tools and material. Obviously, this dependency cannot be predicted by the geometrical approaches.

## Conclusions

The computational model used in this investigative numerical sensitivity study exploits a continuous approach for forming of woven composite based on the hypoelastic behaviour of the fibrous materials. This indeed is a mechanical approach that involves finite element models for macro-scale forming analysis of textile-reinforced materials. Numerical simulations of woven composite reinforcements are performed using two most commonly used forming geometries of HD and double-dome benchmark. Since the continuous composite reinforcements have specific deformation behaviour, the numerical model should be able to predict such deformation mechanisms.

The composite industries involved in the design and manufacture of new products therefore should not rely on the use of simulation tools based on the geometrical approach. The benefits of simplicity in implementation and quick solutions with these tools however do not offset the costs involved in optimization of processing parameters. The effects of processing parameters on the forming results are quite intensive as has been observed with some relevant parametric sensitivity studies such as the present study based on the mechanical approach. The finite element-based mechanical approach has the capacity to predict the influence of processing

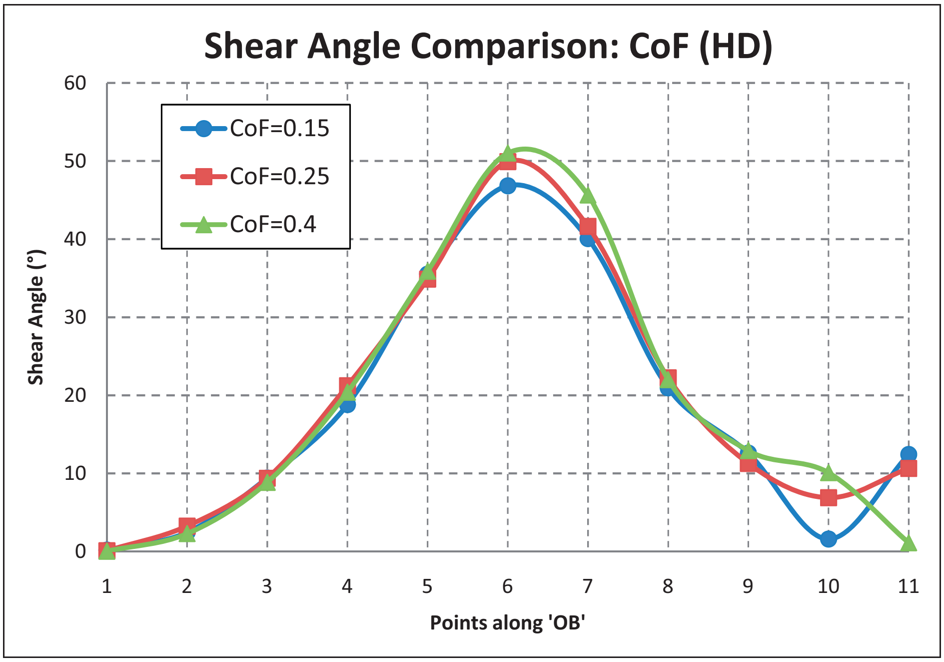

**Figure 15.** Shear angle comparison for three different forming cases over HD model with the initial orientation of fibres as 0°/90° and with CoF as 0.15, 0.25 and 0.4. CoF: coefficients of friction; HD: hemispherical dome.

parameters that hold great value to achieve a successful and almost defect-free product. It has been observed with this particular study that binder force, punch velocity and tool-ply interface behaviour can dominate the forming results. The influence of binder force presented in 'Binder force' section has significantly contributed to alter the material draw-in and resulting shear angles or re-orientation of fibres. Figure 6 shows the effect of unbalanced binder forces predicted through simulation whereas Figure 8 represents the experimental cases to highlight its importance. The binder force applied during forming process induces in-plane stretches to the ply that results in uneven material draw-in, thereby affecting the shearing behaviour of the ply ultimately. The practical implications of forming speed and tool-ply interactions cannot be undermined to obtain a good quality part. Obviously, the selection of a relevant friction model corresponding to the specific materials that can respond towards the influencing factors of slip velocity, normal pressure and temperature would be more useful to predict the actual behaviour during forming. Yet, the recognized fact is that the sensitivity of such parameters can only be predicted with the use of computational models based on finite element analysis.

The forming behaviour of a composite ply (dry or prepreg) is generally linked to its ability to drape onto a surface alternatively dependent upon the architecture of the fibrous reinforcement and sometime on the state of the material.[28] Nevertheless, the quality of forming is largely dependent upon choice of process parameters. Both material and process parameters can indeed be included in the computational models based on mechanical approaches to investigate their influence prior to actual forming.[7,28,29] One of the main objectives of the present study was to demonstrate the sensitivity of processing parameters using hypoelastic computational model and also draw attention of the researchers involved with the development of structural composite products in the new application areas such as automotive.

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