Sensitivity of material properties on wrinkling behavior and fiber reorientation of thermoplastic UD-Tape laminates during forming analyzed by Finite Element forming simulation

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Abstract

Thermoforming plays an increasingly important role in manufacturing of structural composite vehicle components. Nevertheless, a macroscopic buckling and a subsequent wrinkling of the blank is often observed during forming. Additionally, a fiber reorientation is inevitable. Both of these mechanisms emerge in dependence on material properties of the main deformation mechanisms, which namely are shearing and bending of the single ply, as well as friction between the single plies of the stacked laminate. To predict forming behavior by means of Finite Element forming simulation, these mechanisms are modeled via constitutive laws, which facilitates the prediction of the stress and strain distribution during forming, as well as the shape of the formed product. To investigate the influence of the material properties of the above mentioned deformation mechanisms on wrinkling behavior and fiber reorientation, a sensitivity study based on the Design of Experiments (DOE) methodology is conducted. The influence is examined quantitatively by means of Response Surface Methodology on basis of quantitative measures for the examined mechanisms. It could be shown, that for the examined biaxial layup shearing and bending properties have a significant influence and friction between the plies plays a minor role.

1. Introduction

Forming of thermoplastic, multilayered uni-directional (UD) Tape laminates, using high-volume thermoforming processes plays an increasingly important role in manufacturing of structural vehicle components. During forming, fiber reorientation is inevitable and has a large impact on the structural behavior of the finished product. Moreover, the process is often accompanied by a macroscopic buckling and a subsequent wrinkling of the formed blank, which can disqualify the finished product. By means of Finite Element forming simulation, wrinkling and fiber reorientation are predictable, which facilitates to use the simulation for process design. Moreover, forming simulation can be used to improve structural analyses by mapping the predicted fiber orientation to the models used for structural analyses.

The above mentioned mechanisms of wrinkling and fiber reorientation emerge in dependence on material properties of the formed pre-product. More precisely, wrinkling depends on a balance between shear and bending stiffness of the laminate and occurs in regions where the forming tools are not fully closed. To enforce the laminate in the final (double-curved) shape, shear strains are induced in the laminate by closing the forming tools. If shear behavior is too stiff compared to bending

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behavior, the blank will buckle and subsequently develop wrinkles. On the other hand, in-plane fiber reorientation is induced by shear deformation. As these coherences are only qualitative estimates of deformation behavior during forming, a sensitivity study on wrinkling behavior and fiber reorientation is presented for a biaxial layup and a box-shaped generic geometry, similar to the sensitivity study presented by Haanappel [9] for uniaxial layup. The sensitivity study is based on a systematic variation of material properties of the relevant forming mechanisms. For this purpose, Finite Element forming simulation is highly suitable, as deformation mechanisms are reliably modeled via constitutive laws, which are presented in chapter 2. The sensitivity study is conducted based on a FE model setup for which a good coincidence between forming simulation and experimental test has been validated, as presented in chapter 3. To enable a quantitative analysis of the sensitivity study, suitable measures are introduced and the results of the sensitivity study are presented in chapter 4.

2. Finite Element forming simulation

As mentioned before, Finite Element forming simulation offers the possibility of a detailed analysis of the deformation behavior of multilayered thermoplastic blanks during forming, considering material behavior and process conditions. The final shape of the blank, as well as the stress and strain distribution can be predicted due to the modelling of relevant deformation mechanisms (cf. Figure 1) via constitutive laws.

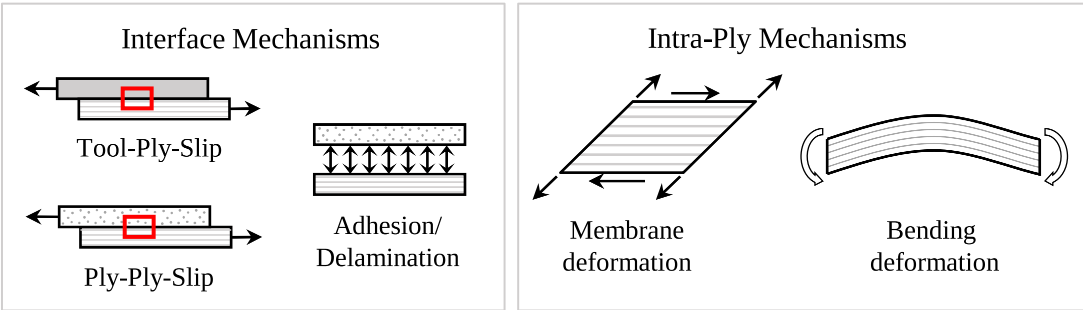

FIGURE 1. Schematic illustration of deformation mechanisms during forming of thermoplastic UD-Tapes.

Besides the deformation behavior of the individual plies of the stacked laminate (intra-ply mechanisms), interface mechanisms between the plies and between the tool and the laminate are modelled via constitutive models. The modelling approaches of these mechanisms are described in the following.

2.1. Interface mechanisms

Interface mechanisms include besides the slip and adhesion between the plies, the interaction between the tool and the formed laminate through normal pressure and surface traction. Prior to the application of the consolidation pressure, the occurring normal pressure and traction at the tool-ply-interface are expected to be low during forming. Hence, the deformation of the tools is also expected to be low, which justifies the modelling of tools as rigid surfaces.

For the implementation of the interface constitutive laws, the Penalty-method [1] is applied to regularize normal and tangential behavior. Moreover, to model normal adhesion and delamination between the individual plies, the Penalty-stiffness is enhanced, as long as a user-defined distance between the plies is not exceeded. For tangential behavior, frictional behavior is modeled in dependence on normal pressure and slip-rate, as these dependencies of frictional behavior could be shown for thermoplastic pre-preg material at process conditions by several authors [2-5]. Therefore, critical stress of a conventional Coulomb frictional law μp [1] is enhanced by a slip-rate-dependent term ηv, as well as by a constant term τ_0, to account for tangential adhesion. This results in the following critical stress for the tangential constitutive law:

$$\tau_{crit} = \tau_0 + \eta v + \mu p. \tag{1}$$

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2.2. Intra-ply mechanisms

For the constitutive modelling of the intra-ply mechanisms, a continuous approach is applied, which uses 2.5D-elements to describe the deformation behavior of single plies. As presented by several authors [6-9], a basic requirement on constitutive laws for intra-ply mechanisms in composite forming is the decoupling of membrane and bending behavior. This is a consequence of the possible relative motion between the fibers at process conditions. Therefore, the thickness-based relation between membrane and bending stiffness given by conventional plate theories is no longer valid. Instead, tensile rigidity in fiber direction is very large in comparison to bending rigidity. To facilitate this decoupling of membrane and bending behavior, separate material models are assigned to membrane and bending behavior. The membrane elements are overlaid with shell elements, where for the shell elements a user-defined integration scheme is applied to include only the plate part of the shell element. The applied constitutive laws for membrane and bending deformation are described in the following.

2.2.1. Membrane deformation

By virtue of large shear deformations during forming and the high anisotropy of the UD-Tapes, the usually applied Green-Naghdi-frame [10], which is based on a polar decomposition of the deformation gradient, is non-applicable for composite forming simulation, as the average rigid body rotation tensor is not unambiguously related to the fiber rotation, as presented by several authors [11, 12]. To overcome this issue, the IFRM (“Ideal Fiber Reinforced Model”) presented by Spencer [13, 14] and successfully applied by Haanappel et al. [15] is applied to model membrane deformation. The constitutive law of IFRM is given by

$$\sigma_{ij} = -p\delta_{ij} + Ta_i a_j + \tau_{ij}, \tag{2}$$

where σ_{ij} is the Cauchy-stress, p an arbitrary hydrostatic pressure inducing an incompressibility condition, T the stress in fiber direction and τ_{ij} an extra stress tensor to model viscoelastic material behavior. For the modelling of the stress in fiber direction, the approach presented by Thije et al. [16] is used, which results in modelling a uniaxial hyperelastic St. Venant-Kirchhoff [10] material in fiber direction.

2.2.2. Bending deformation

Bending behavior of the single ply is modelled using conventional shell elements with a user-defined integration scheme in thickness direction. Following Koiter-Sanders shell theory, the incremental strain tensor at the integration points of the section behavior is given by

$$\Delta\varepsilon_{\alpha\beta} = \Delta\varepsilon_{\alpha\beta}^{mid} + \Delta\varepsilon_{\alpha\beta}^{bend}, \tag{3}$$

which is based on a superposition of the membrane and bending strain increment. The bending strain increment is given by

$$\Delta\varepsilon_{\alpha\beta}^{bend} = F_{33} z \Delta\kappa_{\alpha\beta}, \tag{4}$$

where F_{33} is the component of the deformation gradient in thickness direction, z the distance to the midface and $\Delta\kappa_{\alpha\beta}$ the curvature tensor of the midface. The prediction of the deformation in thickness direction is based on the in-plane deformation and an incompressibility condition of the structural element. The constitutive law is implemented in an orthogonal and fiber parallel frame as presented by several authors [11, 12]. This fiber parallel frame is calculated from fiber rotation in the midface, which can be determined from the deformation gradient in the midface by

$$a_i^1 = F_{ij}^{mid} a_j^0, \tag{5}$$

where a^1_i and a^0_i are the fiber orientation vectors in actual and initial configuration, respectively. To model bending behavior, a Voigt-Kelvin approach is chosen, for which an orthotropic elastic stiffness and an isotropic viscous behavior is assumed.

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3. Validation of Finite Element forming simulation

The previously described methods for Finite Element forming simulation are applied to a box-shaped generic geometry and a biaxial layup. Apparent from figure 2 is a good coincidence between forming simulation and an experimental test with PPS-CF, which is evident from wrinkling and unfolding outside of the mold, as well as of the outer contour of the formed parts.

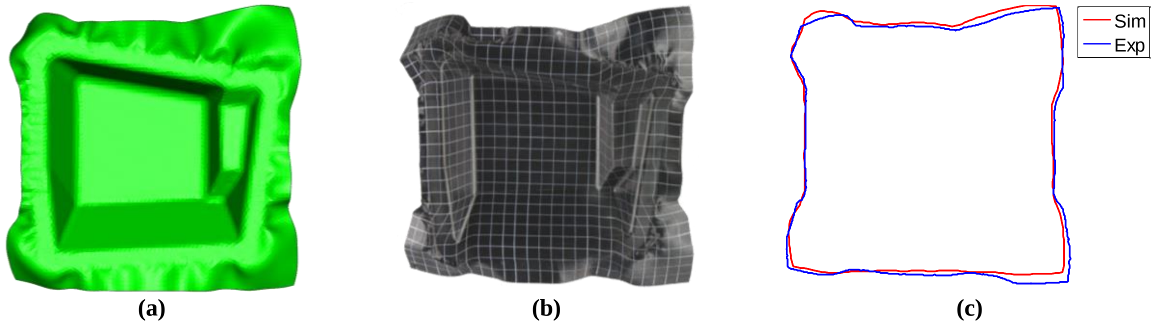


FIGURE 2. Deformed shape predicted by Finite Element forming simulation (a), experimental test for a biaxial PPS-CF layup (b) and comparison of the outer contour of simulation and experimental test (c).

4. Sensitivity study

On basis of the models presented in Chapter 2 and validated in Chapter 3, a sensitivity study on wrinkling behavior and fiber reorientation is conducted, in which the material parameters for membrane, bending and frictional behavior are varied systematically by means of the Design of Experiments (DOE) methodology [18]. For membrane behavior, only in-plane shearing and tension as well as compression perpendicular to fiber direction are affected by the variation of material parameters. Therefore, the fiber modulus is kept constant in this study, as the fiber stiffness is orders of magnitudes higher compared to the other deformation modes and thus will not strongly influence deformational behavior.

For the variation of the material parameters, a face centered composite design [18] is chosen, resulting in 15 investigated configurations (cf. figure 3). For the step width between adjacent configurations, factor 2 is chosen, which means that for configurations of type “+1”, for instance shearing is twice as stiff as the configuration of type “0”.

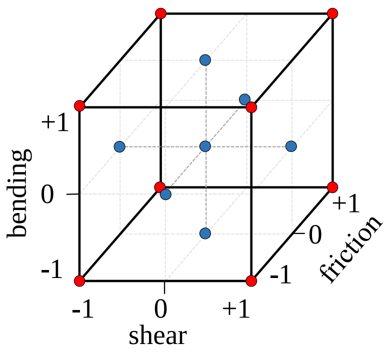


FIGURE 3. Schematic illustration of face centered composite design.

Beyond a qualitative assessment of the sensitivity study, a quantitative evaluation is reasonable. Therefore, the Response Surface Methodology (RSM) [18] is applied, which facilitates to describe the influence of the examined parameters on a target value by a model function, which is chosen to be

$$\Phi = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_{12} x_1 x_2 + \alpha_{23} x_2 x_3 + \alpha_{13} x_1 x_3 . \tag{6}$$

This model function includes linear parameters α_i, which are related to the mean effects shearing, bending and friction, as well as interacting terms α_{ij}, which are related to the coupling between the mean effects. These parameters are determined by a least square fit, based on the values determined for the configurations of the DOE. However, to investigate on wrinkling behavior and fiber orientation, a scalar valued measure is required to describe these effects. Therefore, suitable measures are introduced in chapter 4.1. The results of the fitting to the model function of equation 6, as well as selected simulation results are presented in chapter 4.2.

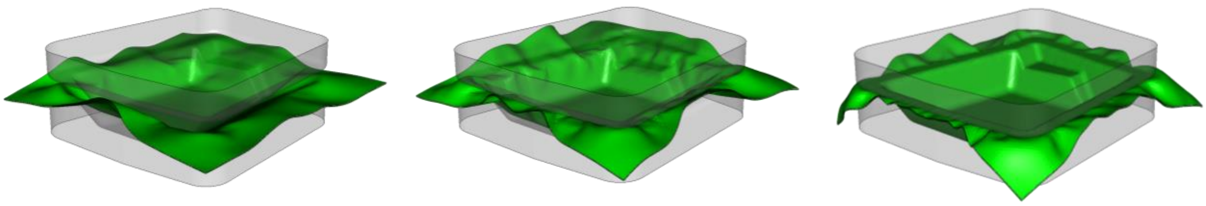
4.1 Quantification measures

Wrinkling: Wrinkling can be regarded as a local curvature of the surface. Therefore, it is reasonable to find a quantitative measure to describe surface curvature on basis of the nodal coordinates, which are a result of Finite Element forming simulation. To do so, a method has been described by Dörr et al. [17], which enables to calculate surface curvature at the nodes of the Finite Element grid.

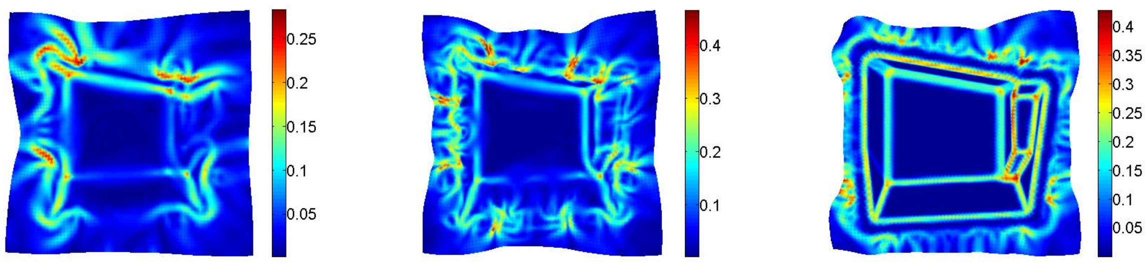
Fiber reorientation: Fiber reorientation can be predicted by means of the deformation gradient (cf. eq. 5). As 2.5D-elements are used for forming simulation, only the in-plane part of the deformation gradient is supplied by the solver. Hence, only in-plane fiber reorientation and no spatial fiber reorientation due to bending deformation of the laminate can be investigated. As solely in-plane fiber reorientation can be inconclusive, the influence on fiber orientation due to shear deformation is investigated. Therefor shear angle is used as quantitative measure, which can be expressed by

$$\Delta\psi = \left| \arctan\left(\frac{F_{21}}{F_{11}}\right) + \arctan\left(\frac{F_{12}}{F_{22}}\right) \right|. \tag{7}$$

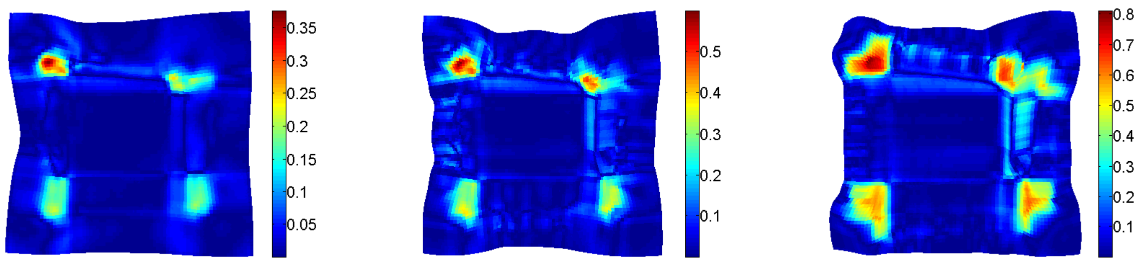
Both of the above mentioned measures are determined by a Matlab Postprocessing as a value field on the deformed geometry, as depicted in figure 4 for several steps during forming simulation.



(a) Tools and deformed geometry



(b) Curvature [rad/mm]



(c) Shear angle [rad]

FIGURE 4. Deformed geometry, curvature and shear angle for three different steps during forming simulation.

To provide a scalar valued measure for the sensitivity study, the mean values of the absolute nodal curvature and of the absolute elemental shear angle of the outer ply are determined. The history of these target values are depicted in figure 5 for the central configuration of the sensitivity study.

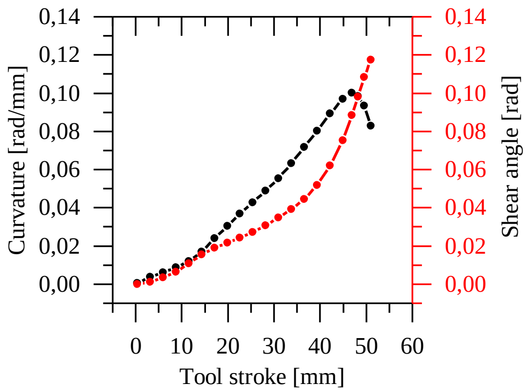
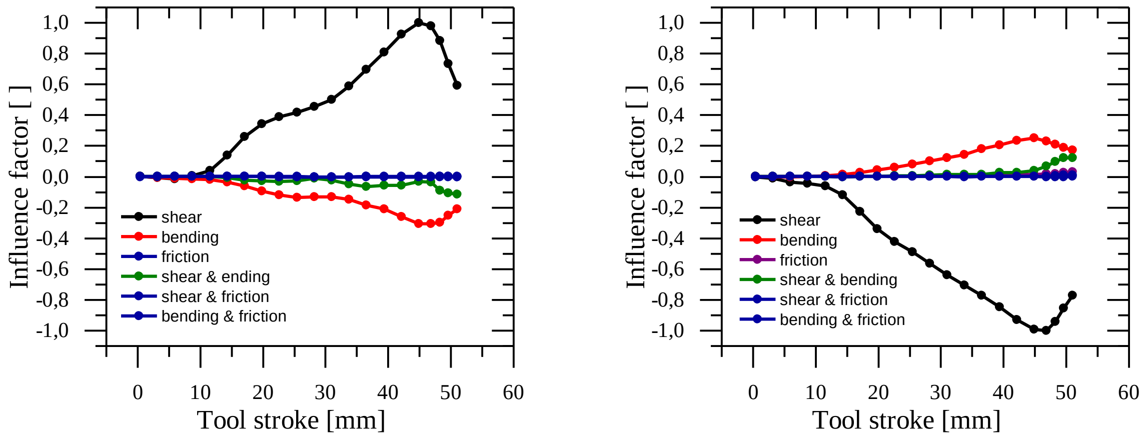


FIGURE 5. Mean value of curvature (black) and of shear angle (red) during forming for the central configuration of the sensitivity study.

Evident from the history of curvature is, that curvature evolves during forming until a maximum, where beyond this maximum wrinkles are reduced by the tooling. Nevertheless, the shear angle is increasing beyond this point, as bending deformation of the wrinkles is transformed into in-plane shear deformation, inducing fiber reorientation.

4.2. Results of the sensitivity study

As result of the sensitivity study, the history of the least square fitted and normalized parameters of the model function (eq. 6) are depicted in figure 6a for surface curvature and in figure 6b for shear angle as target value for several tool stroke positions.



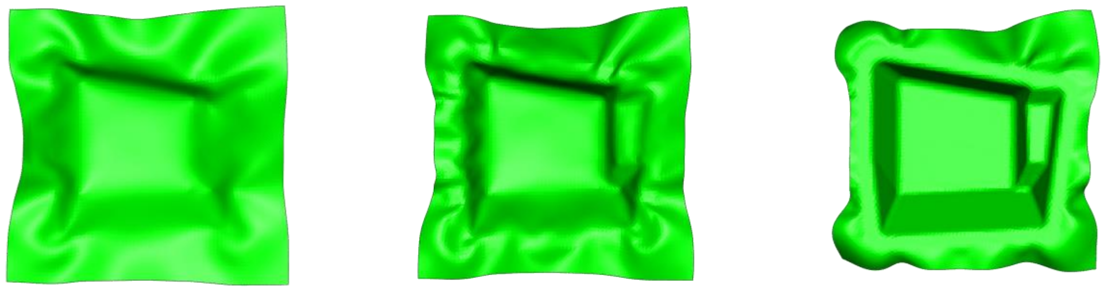
(a) **(b)**

FIGURE 6. Influence factors on wrinkling (a) and shear angle (b).

It turns out, that shear and bending properties have a significant influence on wrinkling and shearing behavior, where a higher shear stiffness and a lower bending stiffness lead to an increase in wrinkling and a decrease of shearing. This contrary relationship can be attributed to that either in-plane shear deformation is feasible to conform to a double-curved geometry or wrinkling occurs if in-plane shear is too stiff. Apparent from the interaction coefficient for shear and bending, this relationship is intensified if properties for shear and bending are changed to opposite directions.
Friction plays a minor role for the evolution of wrinkling and shear deformation, as no distinct influence on the target values is observed for the mean parameter friction and the interaction

parameters including friction. This circumstance is reducible to the biaxial layup examined in the sensitivity study, as no distinct slipping between the plies is observed and shear deformation of the laminate as more or less as a single ply is facilitated. A much more pronounced inter-ply slip is to be expected, if a third fiber direction is present, as outlined by Haanappel [9].

In figure 7, the extremal configurations for wrinkling behavior are depicted, which are the configurations with maximum shear, minimum bending and maximum friction for maximum wrinkling and vice versa.



(a) shear: -1 ; bending: +1 ; friction -1

(b) shear: 0 ; bending: 0 ; friction 0

(c) shear: +1 ; bending: -1 ; friction +1

FIGURE 7. Comparison of central configuration (b) and the configurations with extremal influence (a, c) on wrinkling behavior for three different steps during forming simulation.

5. Summary and Conclusion

A model for Finite Element forming simulation, which is implemented in the commercial multi-purpose Finite Element solver Abaqus, is presented and applied to a box-shaped generic geometry. A good coincidence between forming simulation and an experimental test is observed. The set of material parameters for which the forming simulation result is compared to the experimental test is used for a sensitivity study based on Design of Experiments methodology, for which material properties are varied systematically to investigate the influence of shearing, bending and friction on wrinkling and fiber reorientation. By means of Response Surface Methodology it is shown quantitatively, that shearing and bending properties, as well as the interaction between shearing and bending, have a significant influence on wrinkling and shearing behavior, whereas friction plays a minor role, which is reducible to the examined biaxial layup.

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References

[1] D. Perić and D.R.J. Owen, “Computational Model For 3-D Contact Problems With Friction Based On Penalty Method” in International Journal For Numerical Methods In Engineering, Vol. 35, 1992, pp. 1289–309.
[2] U. Sachs, “Friction and Bending in Thermoplastic Composites Forming Processes”, Dissertation, Universiteit Twente, 2014.
[3] Sachs, U.; Akkerman, R.; Fetfatsidis, K.; Vidal-Sallé, E.; Schumacher, J.; Ziegmann, G. et al., “Characterization of the dynamic friction of woven fabrics: Experimental methods and benchmark results” in Composites Part A: Applied Science and Manufacturing 67, pp. 289–298., 2014.
[4] Murtagh, Adrian M.; Lennon, John J.; Mallon, Patrick J, “Surface friction effects related to pressforming of continuous fibre thermoplastic composites” in Composites Manufacturing 6 (3-4), pp. 169–175, 1995.
[5] Morris S.R. and Sun C.T., “An investigation of interply slip behaviour in AS4/PEEK at forming temperatures” in Composites Manufacturing 5 (4), pp. 217–224, 1994.
[6] E. Guzman-Maldonado, N. Hamila, Boisse, P. Boisse, J. Bikard, “Thermomechanical analysis, modelling and simulation of the forming of pre-impregnated thermoplastics composites”, Composites Part A: Applied Science and Manufacturing 78, pp. 211-222, 2015.
[7] P. Boisse, N. Hamila, E. Vidal-Sallé, F. Dumont, “Simulation of wrinkling during textile composite reinforcement forming. Influence of tensile, in-plane shear and bending stiffnesses”, Composites Science and Technology 71(5), pp. 683-692, 2011.
[8] D. Soulat, A. Cheruet, and P. Boisse. Simulation of continuous fibre reinforced thermoplastic forming using a shell finite element with transverse stress. Computers and Structures, 84(13-14):888–903, 2006.
[9] S. Haanappel, “Forming of UD fiber reinforced thermoplastics – a critical evaluation of intra-ply shear, Dissertation, Universiteit Twente, 2013.
[10] T. Belytschko, W. K. Liu, B. Moran, K. Elkhodary, “Nonlinear Finite Elements for Continua and Structures”, John Wiley & Sons, Inc., 2013.
[11] A. Willems, “Forming simulation of textile reinforced composite shell structures”, Dissertation, Katholike Universiteit Leuven, 2008.
[12] P. Badel, E. Vidal-Sallé, P. Boisse, “Large deformation analysis of fibrous materials using rate constitutive equations”, Computers and Structures 86, pp. 1164-1175, 2008.
[13] A. Spencer, “Deformation of Fibre-Reinforced Materials” in Oxford, Clarendon Press, 1972.
[14] A. Spencer, “Theory of fabric-reinforced viscous fluids” in Composites: Part A 31, pp. 1311–21, 2002.
[15] S.P. Haanappel, R. ten Thije, U. Sachs, B. Rietman and R. Akkerman, “Formability analyses of uni-directional and textile reinforced thermoplastics” in Composites: Part A 56, pp. 80-92, 2014.
[16] R. ten Thije, R. Akkerman and J. Huétink. “Large deformation simulation of anisotropic material using an updated Lagrangian finite element method” in Comput. Methods Appl. Mech. and Engrg. 196, pp. 3141-3150, 2007.
[17] D. Dörr, T. Joppich, F. Schirmaier, T. Mosthaf, L. Kärger, F. Henning, “A Method for Validation of Finite Element Forming Simulation On Basis of a Pointwise Comparison of Distance and Curvature”, Key Engineering Materials – ESAFORM 2016 (Nantnes).
[18] K. Siebertz, D. van Bebber, T. Hochkirchen, “Statistische Versuchsplanung”, Springer-Verlag Berlin Heidelbert, 2010.

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