

History and future of composites forming analysis

R Akkerman^{1,2}, S P Haanappel³ and U Sachs¹

¹TPRC, PO Box 770, 7500 AT Enschede, The Netherlands

²University of Twente, PO Box 217, 7500AE Enschede, The Netherlands

³Aniform, Palatijn 15, 7521PN Enschede, The Netherlands

Abstract. The developments of composites forming analyses are summarized, from a historic perspective and towards the expected future. While the recent methods are already accepted in the market, there is a number of challenges ahead in simulation methods and experimental characterisation, to reach even better predictions of defects and part distortions.

1. Introduction

Rapid manufacturing processes such as hot press forming of thermoplastic composites are key technologies for large scale composite applications to emerge. Typically, tool manufacturing is time consuming and the tooling costs are high, having a large impact on the development time and cost of new press formed parts. For products to be successful on the market, trial-and-error development should be prevented. Composites forming simulations provide a means to prevent or reduce these costly iterations to a bare minimum, and are in this sense crucial for a mature position of composites on this market for high volume manufacturing. Overseeing the past and the present, it can be observed that the applications of composite materials go hand-in-hand with the developments in simulation tools. It is to be expected that this also holds for the upcoming stage of coming to maturity, requiring predictive design tools and quality control which can be supported by further improved and extended simulation methods.

2. History

Fibre composites provide the potential for structural optimisation by means of orienting the fibres in their most favourable direction. The positioning of the fibres themselves, however, depends strongly on the manufacturing process. Fibre placement, for instance, provides great flexibility in fibre positioning, primarily constrained by the continuity of the fibres which should not change orientation in a stepwise manner from one location to another. A higher speed of fibre deposition can be achieved by using multiple tows simultaneously as in braiding, by using broader tape or by using textiles such as woven fabrics. Each approach generates its own constraints on the achievable fibre orientation distribution over the part to be manufactured.

Woven fabrics further provide great ease of handling and, depending on the fabric architecture, good drapeability. The same goes for random mats of continuous or discontinuous fibres, in which case there is little use of preferred fibre orientations, however. Early applications of fibre composites relied on manual lay-up of such mats and fabrics, on which a thermoset resin was applied to impregnate the fibres. By means of manual lay-up, the laminator can prevent the occurrence of defects such as wrinkling to some extent and, in case of fabrics, can steer the fibres in favourable directions. Early work on the analysis of drapeability of fabric plies dates back to the 1950s [1], more or less simultaneous to the development of the materials and processes involved. Ever since, the composites research and development have kept a close link between materials, processes and design aspects, including the



underlying analysis methods. In this case, mapping schemes were developed to project a pin-jointed net on the tool geometry, providing a means to predict the fibre orientations and fabric shear as a result of draping for specific geometries in closed form. Since the pioneering analytical work by Mack and Taylor, many authors used the ‘fishnet approach’ for numerical simulations of the draping process, e.g. [[2]-[7]]. Typically, these drape models start from an arbitrary initial point and two initial fibre directions. Further points are then generated at a fixed equal distance from the previous points, creating a mesh of quadrilateral cells.

There is no unique solution for this geometrical drape method, as the solution depends on the chosen sequence of cells to be generated. This problem is generally solved by defining two fibre paths on the drape surface, from which the cells will be generated. Bergsma [6] introduced ‘strategies’ in order to find solutions for the drape algorithm, without pre-defining such fibre paths, and also included a mechanism to incorporate the locking phenomenon in his drape simulations. Iterative approaches to account better for the actual shear characteristics of the fabrics have been proposed [8]-[9], using local energy minimisation for each new set of cells to be added to those generated previously. In this way, the material behaviour can be represented to a certain extent, while retaining the very fast solver times of the geometric approach.

These essentially geometry-based methods cannot easily represent the actual material behaviour in great detail. Not accounting for the through-thickness interactions between the layers, are they not very well suited for simulations of forming multi-layered laminates at once, in which the inter-ply friction plays an important role. Also the interactions with blank holders and tool surfaces cannot easily be included in these mapping schemes. Such interactions can be implemented more easily in Finite Element representations, at the cost of significantly higher computation time.

Alternatively, a fabric can be represented as a collection of particles [10] with e.g. elastic or plastic interactions, representing energy contributions due to thread repelling, thread stretching, thread bending, thread trellising and gravity. Constraints can be used to prevent intersection of the particles with rigid bodies such as the surface on which the fabric is to be draped. Fast algorithms have been developed to simulate cloth behaviour on dressed virtual humans in real time, see e.g. [11]. Intended for virtual impressions of apparel fabric rather than detailed studies of the local deformations, these methods have not seen implementation in the technical industry to the authors’ knowledge.

Finite Element representations for composites forming processes have been developed from the 1990s. The early formulations adopted orthotropic elastic material behaviour in continuum shell elements [12]-[14] to model e.g. the draping of a cloth on a table. An early multi scale approach was presented in [15], using a thermomechanically coupled scheme for an anisotropic fluid with anisotropic thermal properties, where these properties were solved using micromechanical modelling of RVEs with the appropriate fibre orientations. Alternatively, truss based schemes have been presented, with the trusses representing the stiff fibres (albeit in tension) and an underlying membrane representing the inplane shear behaviour [16],[17]. Also mesoscopic analyses have been performed, to analyse the interaction of fibres, possibly impregnated and possibly with the resin rich areas. In these, the material behaviour of the tows is non-trivial and not easily characterised experimentally. Nevertheless, the simulations provide useful insight in the origins of macroscopically observed behaviour.

Fairly rapidly, the technology of forming simulation software and associated material characterisation has found its way into commercial software and services, supporting composite manufacturing of press formed fibre reinforced thermoplastic parts. Early approaches adopted the geometric mapping schemes (in e.g. Fibersim and similar packages), later also specific tools became available using explicit FE solvers (PAM-Form) and implicit FE solvers (Aniform). The large deformations and the extremely anisotropic behaviour of composite materials in forming conditions give rise to significant challenges with respect to stable convergence and accuracy [18]. These FE models are primarily used on the macroscopic scale, treating a ply or a group of plies as an anisotropic continuum, represented in plate or shell elements.

Long [19] presented an overview of the deformation mechanisms in composite laminates during forming. Figure 1 provides an illustration of such a classification. Of these mechanisms, the current FE

descriptions typically include trellis shear (described as a viscous, elastic or viscoelastic phenomenon), inter-ply and tool/ply friction (described with a coefficient of friction or a viscous slip coefficient, which may depend on rate, pressure and temperature) and bending (usually described as an elastic phenomenon with an appropriate bending modulus). All require specific experimental techniques and procedures to determine the relevant material property data.

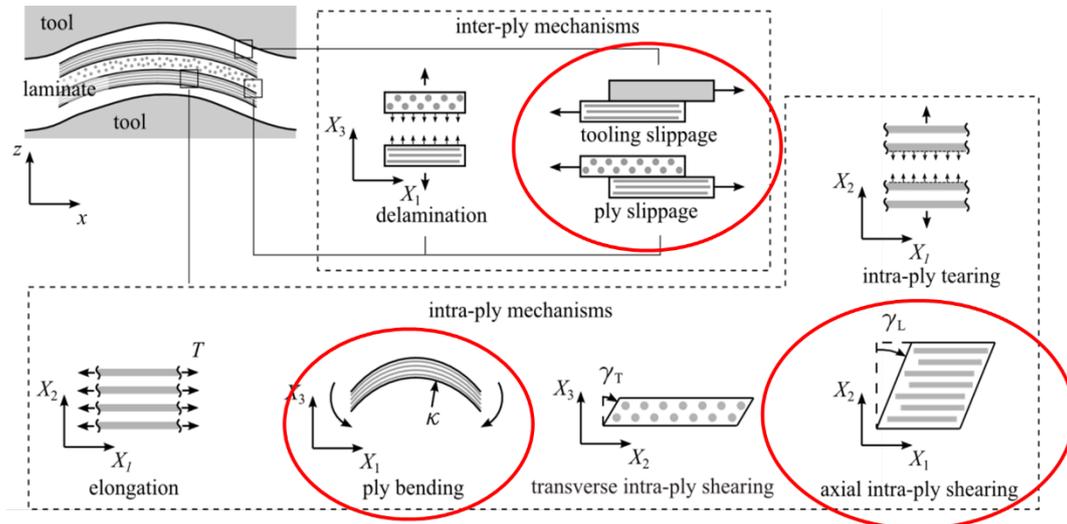


Figure 1. Deformation mechanisms in (unidirectional) composite laminates.

Early publications by Boisse and co-workers focused on the response of fabrics due to bi-axial tension in the fibre directions [14], for which an experimental set-up was developed and the nonlinear response was measured and included in the forming simulation model. Subsequently, the focus moved towards the inplane trellis shear response, in particular on normalising the results for different specimen sizes and on developing standards for obtaining operator and equipment independent test results. The modelling efforts were in particular devoted to rate independent behaviour of dry fabrics, typically described in terms of the normalised shear force as a polynomial function of the shear angle [20]. Benchmarking activities were performed not only on inplane shear [21] but also on friction [22] and forming simulations and experiments on a benchmark ‘double dome’ geometry [23]-[27].

3. Current trends in material modelling

While the process simulations have found their way into industrial application, this does not imply that the composites forming software is infallible. Not all possible deformation mechanisms are included in the current software, and there is ample room for improvement of the models of the mechanisms that are included already.

Thermoplastic laminates are conventionally made by consolidation of plies at high temperature and pressure, in order to minimise porosity in the laminate. It may come as no surprise that this leads to residual stresses that will attempt to de-consolidate the laminate when returning to melt temperature in the forming process. Early publications [28] addressed this phenomenon, but the effects of this changing state on the other deformation mechanisms have been hardly investigated. Slange [29] shows in a recent publication that the preconditioning of the consolidated laminates (drying but also annealing at high temperatures) has a strong effect on the amount of deconsolidation. Accurate quantitative description and predictive modelling of these phenomena requires significant further research efforts.

Inter-tow slippage is another mechanism that is observed to play a role [30] during laminate tensioning, but rarely modelled. An early continuum FE model by Ten Thije capturing this kind of fibre slip in non-crimp fabrics [31] has found little follow up, and also mesoscopic descriptions are found

primarily in the research domain, but not in generically available design for composite manufacturing software.

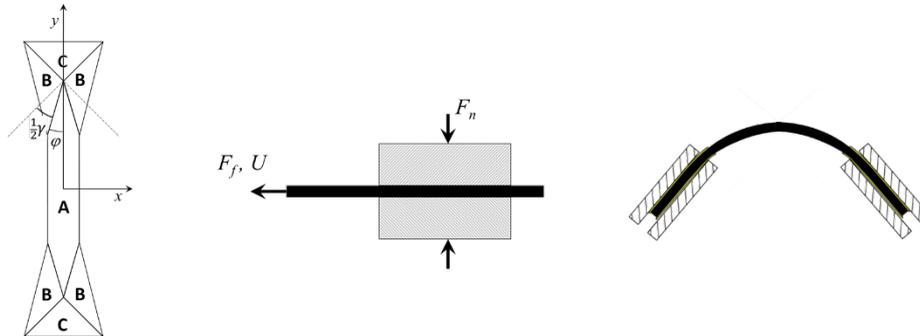


Figure 2. State of the art material characterisation methods (schematically) for uniaxial bias extension, tool/ply (and ply/ply) friction, bending (torsional rheometry).

The usually implemented mechanisms include trellis shear (described as a viscous, elastic or viscoelastic phenomenon), friction (described with a coefficient of friction or a viscous slip coefficient, which may depend on rate, pressure and temperature) and bending (usually described as an elastic phenomenon with an appropriate bending modulus). Figure 2 schematically illustrates some typical experiments for the associated material characterisation. Although good progress has been made over the years, the constitutive models are simplified representations of the actual material behaviour. This is, however, closely linked to the availability of accepted material characterisation methods and the associated material property databases for the growing range of materials available on the market. Further, the models employed so far are primarily isothermal, which is a fair approximation in many cases. However, the need for non-isothermal models is apparent when trying to predict shape distortions due to process induced residual stresses. The same holds for defect prediction. Forming induced large wrinkles and folds can be predicted well by the current approach, but wrinkles smaller than the element size require further advanced criteria, simulations and related material property data.

Inplane shear testing can be considered the most researched subject in fabric composite characterisation. Picture Frame (PF) and Uniaxial Bias Extension (UBE) tests are most often applied in this respect. The former generally suffers from lack of control of the fibre tension, which is likely to affect the shear response, whereas the latter involves non-uniform deformations which complicates the analysis of the results. In addition, UBE inherently invokes fibre tension together with shear, such that the ‘zero-tension’ situation cannot be tested with this method. In its simplest form, the effects of fibre tension on the shear behaviour are neglected and the resistance to shear is described as a path independent function of the local shear angle only. The accepted approach uses a power equilibrium method to derive the material property data from a bias extension test. Adding simple force equilibrium considerations to this approach [32] leads to tight constraints for the force-displacement and stress-strain relations of which the consequences are not fully understood to date. Even this very basic case has not been fully resolved yet.

Harrison et al. [33] presented a Biaxial Bias Extension (BBE) test by which the effect of tension on the shear response can be quantified under constant transverse loads. PF experiments with tensioners were presented by Nosrat-Nezami et al [34], showing significant non-linear effects of both uniaxial and biaxial tension on the shear response. The effects of these interactions on the forming behaviour was shown in [35] for rate independent materials by means of FE simulations using an Abaqus user material model.

Considering the contact area between successive plies and between the laminate and the tool, it comes as no surprise that friction has a large effect on the formability of composite laminates. Where friction of dry fabrics may still be described with a rate independent Amonton/Coulomb coefficient of friction, this is not applicable to impregnated fabric composites. In this case, the steady state tool/ply friction can be modelled well by means of hydrodynamic lubrication theories on the meso scale, predicting the

macroscopic sliding resistance with the textile geometry, the matrix viscosity and the exerted normal pressure as the input [36]. Ply/ply friction measurements of textile plies in general depict a similar hydrodynamic behaviour. Friction measurements were benchmarked in [37], where only few set-ups were able to characterise thermoplastic laminates in forming conditions.

Sliding friction measurements in general show a clearly time dependent response (see figure 3).

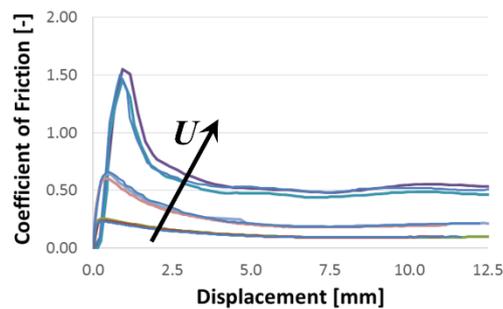


Figure 3. Sliding friction test results for tool/ply contact of 5HS C/PPS at 310°C, 50kPa and displacement rates of 20, 100, 500 mm/min.

The frictional force increases gradually to a steady state value for very low sliding velocities, but shows an (increasing) overshoot as the sliding velocity increases. Both the peak friction and the steady state friction are in the hydrodynamic range for both ply/ply and tool/ply friction, as demonstrated in e.g. [38]. However, a single coefficient of friction is clearly not equal to the transient response as actually measured. Further, the assumption of hydrodynamic lubrication due to flow of the matrix material is obviously not applicable for temperatures below T_m (assuming semi-crystalline matrices). In this case another mechanism applies, that of a solid fibre reinforced polymer sliding on a metallic substrate. Also this situation is temperature dependent (although less pronounced than above T_m), certainly when the polymer crosses the glass transition during the process. Finally, the condition of the tool surface will affect the sliding response below T_m . Careful characterisation is required for accurate process modelling, which needs to be able to account for all relevant details!

Bending of laminates is the third deformation mechanism usually considered. Standard shell elements would describe the behaviour of a laminate as being elastic, i.e. rate independent. As interply slip dominates the laminate bending behaviour, it is obvious that the resin viscosity plays an important role in this mechanism, which hence can be expected to be rate dependent. The common quasi static flexural tests, monitoring the bending of a laminate under its own weight, cannot easily be interpreted to determine such rate dependency. Rheometer bending tests such as proposed in [39] do offer this possibility. The characteristic responses can be captured in a viscoelastic model, essentially leading to a relation between the bending moment, the curvature and the transverse shear rate. Alternatively, a multi-mode nonlinear viscoelastic model can be formulated and fitted on bending experiments [40] to describe the relation between the bending moment and the evolution of the bending angle. As indicated in [41], the obvious approach requires a time dependent Mindlin-type formulation, specific for fibre composite laminates in forming conditions.

As a final remark on the continuously advancing field of constitutive modelling and material characterisation, also the translation from experiment to material property data can be non-trivial. Not every combination of characterisation experiment and constitutive model has a closed form relation between the data measured, with a unique solution ('best fit') for the material property data to be determined. This often calls for nonlinear iterative procedures, either using approximate analytical expressions or more elaborate numerical analyses simulating the experiment in more or less detail. These parameter identification methods (fitting material property data such that simulations of experiments agree with measured force-displacement data) provide a way to determine these data for arbitrary

constitutive equations, also those including nonlinear temperature and rate dependency. The results of such analyses may, however, depend on the initial guess, as there is often no guaranteed unique solution for the nonlinear equations involved. In general, as in any parameter fitting procedure, interpolation within the measured range is usually acceptable, but extrapolation beyond this range is debatable.

4. Towards defect prediction methods

Considerable progress has been made over the past two decades to enable predictive simulations of thermoplastic composite stamp forming processes with largely reliable outcome, provided the material property data has been measured and modelled accurately and provided that the boundary conditions imposed during the process are properly modelled. This serves primarily the purpose of predicting large processing defects such as wrinkles and folds, spanning multiple elements. Defects of a smaller size are not easily predicted yet, which attracts the attention of various research groups.

In a broad sense, processing induced defects include ply splitting/transverse cracks, matrix degradation, voids, dry spots, delamination, surface defects (due to severe traction or resin squeeze out), contamination, fibre distortions (folds, wrinkles and waviness) and fibre breakage. All defects affected by the local pressure during forming require an accurate pressure prediction, which in turn is strongly dependent on the thickness variation due to shear deformation of the laminate and the local cavity thickness (in particular when using two sided rigid tooling). This is well within range of current modelling capabilities. Second order effects such as tool deflections are outside the range of phenomena than can be predicted with conventional analyses.

Accurate descriptions of some of these defects require full thermomechanical modelling, including the prediction of residual stresses at the meso or micro level as well as the criteria for crack initiation and growth at all temperatures involved in the case of transverse cracks and delaminations. The latter criteria may require simple temperature dependent transverse strength values and/or critical energy release rates (possibly as a function of the consolidation state, fibre angles, ...) over the same range from room temperature up to the forming temperature. This is beyond current modelling capabilities. Nevertheless, the current simulation results can already be utilised to check for indications for certain defects. Large transverse strains indicate ply splitting in unidirectional plies, high fibre stresses on rounded edges indicate resin squeeze out (figure 4), the possibility of fibre breakage is clearly indicated by (extremely) high fibre stresses and low pressure is an indicator for poor consolidation quality (including porosity and surface defects, see figure 5).

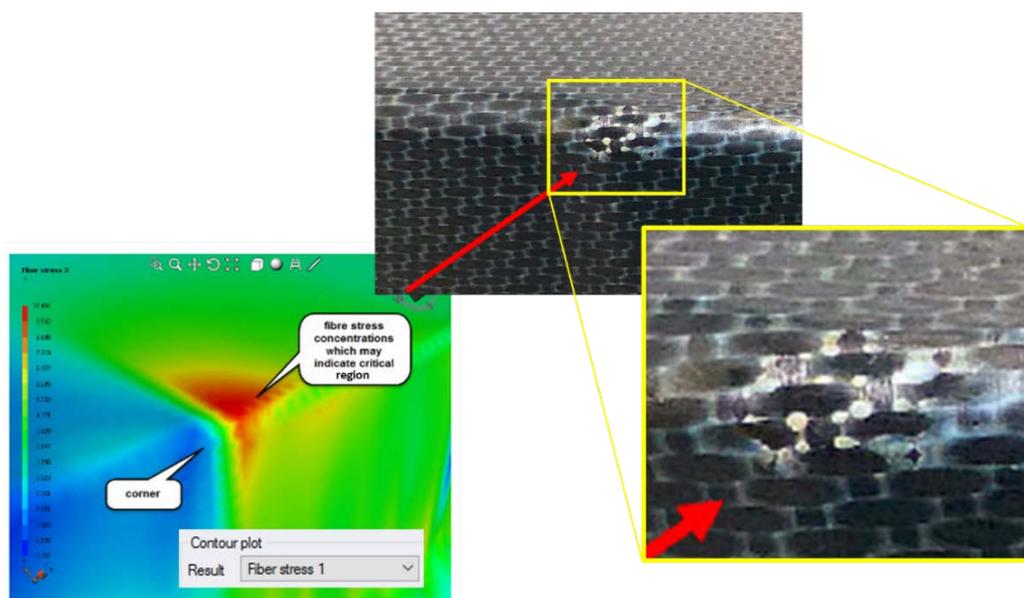


Figure 4. Predicted fibre stresses (left) are an indicator for resin squeeze out (right).

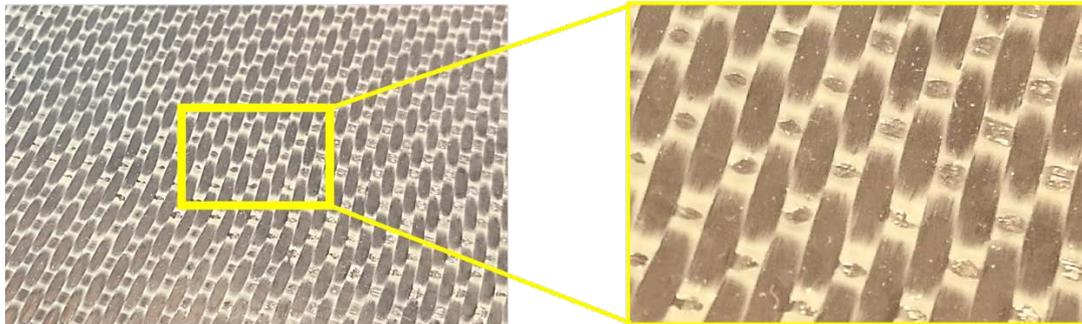


Figure 5. Poor consolidation quality due to insufficient laminate pressure.

The defects having received most attention, nevertheless, are wrinkles of different scales: from fibre waviness in- and out-of-plane to small wrinkles in some plies or in the laminate as a whole up to large folds in the final product. Already in an early stage, Gutowski et al [42] addressed laminate wrinkling during double diaphragm forming as caused by compression when deforming a laminate on a doubly curved tool, and using a mapping based scheme to quantify the amount of compression. Nonlinear FE simulations are well able to predict this kind of buckling phenomena, provided there are sufficient elements to describe the typical shape (see figure 6).

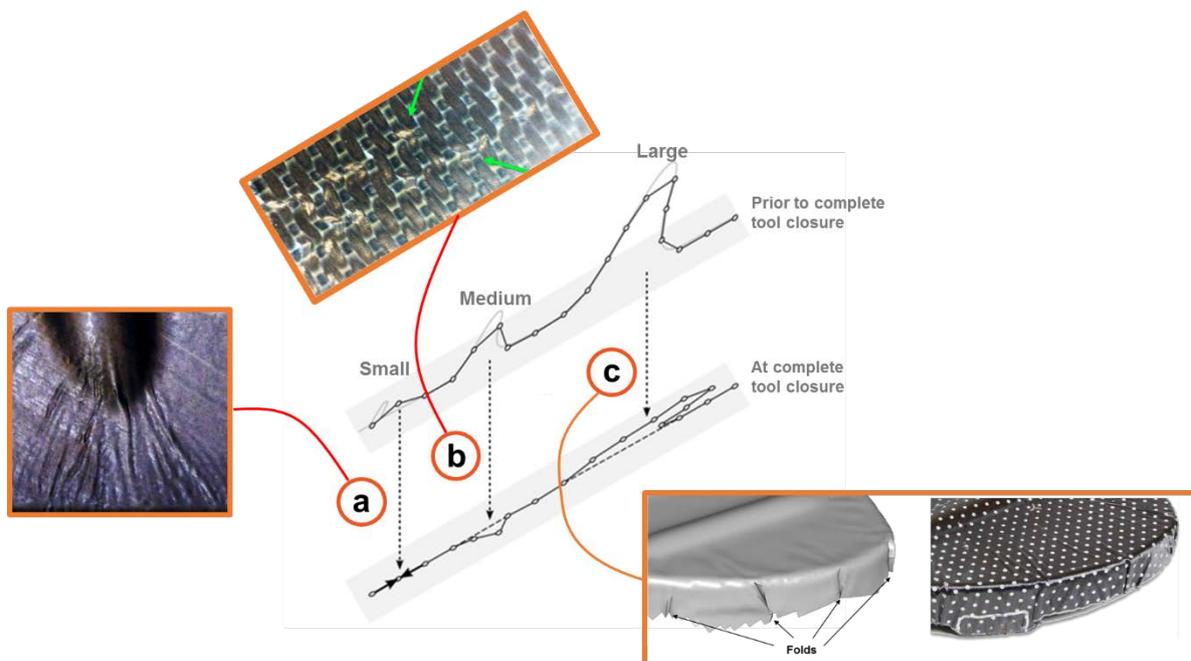


Figure 6. Development of fibre distortion defects of different sizes during tool closure.

Wrinkles smaller than an element can obviously not be described in an ordinary element displacement field ('a' in figure 6). However, the associated compressive stresses may well show up in the final result, which can be used as an indicator showing the risk for such small wrinkles/waviness. To date, to the authors' knowledge, there is not yet a reliable criterion and associated material characterisation technique to predict the waviness of this kind using current FE simulations of the composites forming process. A first attempt towards a Forming Limit Diagram was presented in [46], illustrating the challenges yet to overcome. Slightly larger wrinkles ('b' in figure 6) may disappear in the time step when the tools are totally closed, but which still show up in the actual stamp formed part as inplane waviness. These are easily observed in unidirectional materials, but can also be distinguished

fabric composites with some more effort (see the ‘Medium’ example in figure 6). Simulation results typically show checkerboard patterns of the inplane shear angle when this phenomenon occurs. The larger wrinkles (‘c’ in figure 6) can be captured fairly well in current FE tools, despite all limitations of the constitutive models employed (see also [43]), and although a sensitivity study in [44] showed that the predicted deformations and defects are ‘the result of a delicate balance between the shear, bending, and friction mechanisms considered’. Characterising the material in the right range of deformations and deformation rates may conceal underlying imperfections, such as using an elastic model for the essentially visco-elastic material behaviour during bending.

5. Conclusion

As shown in this paper, composites forming simulations have well advanced over the past decades, leading to accessible ‘design for composite manufacturing’ software tools which are maturing rapidly, enabling cost-effective composite part development. Ongoing efforts on material property databases will further support this advancement. The next stages in defect prediction methods are challenging, with respect to constitutive modelling, Finite Element formulations, material characterisation techniques and reliable defect indicators. The current research efforts worldwide, however, stimulated by the growth of thermoplastic composite applications, lead to good prospects for continued progress in the years to come.

Acknowledgements

The authors gratefully acknowledge the financial as well as technical support from the industrial and academic members of the ThermoPlastic composites Research Center (TPRC) as well as the support funding from the Province of Overijssel for improving the regional knowledge position within the Technology Base Twente initiative.

References

- [1] Mack C and Taylor H (1956), ‘The fitting of woven cloth to surfaces’, *Journal of Textile Institute*, 47, 477-487.
- [2] Robertson RE, Hsiue ES and Yeh GSY (1984), ‘Fibre rearrangements during the moulding of continuous fibre composites II’, *Polymer Composites*, 5, 191-197.
- [3] Smiley AJ and Pipes RB (1988) ‘Analysis of the diaphragm forming of continuous fiber reinforced thermoplastics’, *Journal of Thermoplastic Composite Materials*, 1, 298-321.
- [4] Heisey FL and Haller KD, ‘Fitting woven fabric to surfaces in three dimensions’, *Journal of the Textile Institute*, 1988, 2, 250-263.
- [5] Long AC and Rudd CD (1994) ‘A simulation of reinforcement deformation during the production of preforms for liquid moulding processes’, *Journal of Engineering Manufacture*, 208, 269-278.
- [6] Bergsma O (1995), Three-dimensional Simulation of Fabric Draping, PhD thesis Delft University of Technology.
- [7] Trochu F, Hammami A and Benoit Y (1996), ‘Prediction of fibre orientation and net shape definition of complex composite parts’, *Composites Part A*, 27, 319-328.
- [8] Long AC, Clifford MJ, Harrison P and Rudd, CD (2001), ‘Modelling of draping and deformation for textile composites’, *ICMAC–international conference for manufacturing of advanced composites*, Belfast, IOM Communications, 66-76.
- [9] Sharma SB and Sutcliffe MPF (2003), ‘Draping of woven fabrics: Progressive drape model’, *Plastics, rubber and composites*, 32(2), 57-64.
- [10] Breen D, House D and Wozny M (1994), ‘A particle-based model for simulating the draping behavior of woven cloth’, *Textile Research Journal*, 64, 663-685.
- [11] Cordier F and Magnenat-Thalmann N (2002), ‘Real-time animation of dressed virtual humans’ *Computer Graphics Forum (Eurographics 2002)*, 21, 327-336.
- [12] Chen B, and Govindaraj M (1995), ‘A physically based model of fabric drape using flexible shell

- theory', *Textile Research Journal*, 65, 324-330.
- [13] Kang T and Yu W (1995), 'Drape simulation of woven fabric by using the finite element method', *Journal of the Textile Institute*, 86, 635-648.
- [14] Boisse P, Borr M, Buet K and Cheroaut A (1997), 'Finite element simulation of textile composite forming including the biaxial fabric behaviour', *Composites Part B*, 28, 453-464.
- [15] Hsiao SW and Kikuchi N (1999), 'Numerical analysis and optimal design of composite thermoforming process', *Computer methods in applied mechanics and engineering*, 177(1-2), 1-34.
- [16] Lin H, Wang J, Long AC, Clifford MJ and Harrison P (2007), 'Predictive modelling for optimization of textile composite forming', *Composites Science and Technology*, 67(15-16), 3242-3252.
- [17] Skordos AA and Sutcliffe MP (2008), 'Stochastic simulation of woven composites forming', *Composites Science and Technology*, 68(1), 283-296.
- [18] Ten Thije RHW, Akkerman R and Huétink J (2007), 'Large deformation simulation of anisotropic material using an updated Lagrangian finite element method', *Computer methods in applied mechanics and engineering*, 196(33-34), 3141-3150.
- [19] Long, AC (Ed.) (2014), *Composites forming technologies*. Elsevier.
- [20] Harrison P, Fernandez Alvarez M, Anderson D (2017), 'Towards comprehensive characterisation and modelling of the forming and wrinkling mechanics of engineering fabrics', *International Journal of Solids and Structures*, accepted for publication.
- [21] Cao J, Akkerman R, Boisse P, Chen J, Cheng HS, de Graaf EF, Gorczyca JL, Harrison P, Hivet G, Launay J, Lee W, Liu L, Lomov SV, Long A, de Luycker E, Morestin F, Padvoiskis J, Peng XQ, Sherwood J, Stoilova Tz, Tao XM, Verpoest I, Willems A, Wiggers J, Yu TX and Zhu B (2008), 'Characterization of mechanical behavior of woven fabrics: experimental methods and benchmark results', *Composites Part A: Applied Science and Manufacturing*, 39(6), 1037-1053.
- [22] Sachs U, Akkerman R, Fetfatsidis K, Vidal-Sallé E, Schumacher J, Ziegmann G, Allaoui S, Hivet G, Maron B, Vanclooster K and Lomov SV (2014) 'Characterization of the dynamic friction of woven fabrics: experimental methods and benchmark results', *Composites Part A: Applied Science and Manufacturing*, 67, 289-298.
- [23] Willems A, Lomov SV, Verpoest I, Vandepitte D, Harrison P and Yu WR (2008), 'Forming simulation of a thermoplastic commingled woven textile on a double dome', *International Journal of Material Forming*, 1(1), 965-968.
- [24] Khan MA, Mabrouki T, Vidal-Sallé E and Boisse P (2010), 'Numerical and experimental analyses of woven composite reinforcement forming using a hypoelastic behaviour. Application to the double dome benchmark', *Journal of materials processing technology*, 210(2), 378-388.
- [25] Peng X and Rehman ZU (2011), 'Textile composite double dome stamping simulation using a non-orthogonal constitutive model', *Composites Science and Technology*, 71(8), 1075-1081.
- [26] Rietman B, Haanappel SP, ten Thije RHW and Akkerman R. (2012), 'Forming simulation sensitivity study of the double-dome benchmark geometry', In *Key engineering materials* (Vol. 504, pp. 301-306), Trans Tech Publications.
- [27] Harrison P, Gomes R and Curado-Correia N (2013), 'Press forming a 0/90 cross-ply advanced thermoplastic composite using the double-dome benchmark geometry', *Composites Part A: Applied Science and Manufacturing*, 54, 56-69.
- [28] Soulat D, Cheruet A and Boisse P (2006), 'Simulation of continuous fibre reinforced thermoplastic forming using a shell finite element with transverse stress', *Computers & structures*, 84(13-14), 888-903.
- [29] Slange TK, Warnet LL, Groupe WJB and Akkerman R (2018), 'Deconsolidation mechanisms during stamp forming of C/PEEK blanks', *Composites Part A: Applied science and manufacturing*, accepted for publication.
- [30] Boisse P, Hamila N, Guzman-Maldonado E, Madeo A, Hivet G and Dell'Isola F (2017), 'The

- bias-extension test for the analysis of in-plane shear properties of textile composite reinforcements and prepregs: a review', *International Journal of Material Forming*, *10*(4), 473-492.
- [31] Ten Thije RHW, Loendersloot R and Akkerman R (2005), Drape simulation of non-crimp fabrics, in *ESAFORM 2005: 8th ESAFORM Conference on Material Forming*, The Publishing House of the Romanian Academy.
- [32] Akkerman R (2018) A continuum mechanics analysis of shear characterisation methods, *Composites Part A: Applied Science and Manufacturing*, *109*, 131-140.
- [33] Harrison P, Abdiwi F, Guo Z, Potluri P and Yu, WR (2012), 'Characterising the shear-tension coupling and wrinkling behaviour of woven engineering fabrics', *Composites Part A: Applied science and manufacturing*, *43*(6), 903-914.
- [34] Nosrat-Nezami F, Gereke T, Eberdt C and Cherif C (2014), 'Characterisation of the shear-tension coupling of carbon-fibre fabric under controlled membrane tensions for precise simulative predictions of industrial preforming processes', *Composites Part A: Applied Science and Manufacturing*, *67*, 131-139.
- [35] Komeili M and Milani AS (2016), 'On effect of shear-tension coupling in forming simulation of woven fabric reinforcements', *Composites Part B: Engineering*, *99*, 17-29.
- [36] Ten Thije RHW, Akkerman R, Ubbink M and Van der Meer L (2011), 'A lubrication approach to friction in thermoplastic composites forming processes', *Composites Part A: Applied Science and Manufacturing*, *42*(8), 950-960.
- [37] Sachs U, Akkerman R, Fetfatsidis K, Vidal-Sallé E, Schumacher J, Ziegmann G, Allaoui S, Hivet G, Maron B, Vanclooster K and Lomov, SV (2014), 'Characterization of the dynamic friction of woven fabrics: experimental methods and benchmark results', *Composites Part A: Applied Science and Manufacturing*, *67*, 289-298.
- [38] Akkerman R, Ten Thije R, Sachs U and De Rooij M (2010), 'Friction in Textile Thermoplastic Composites Forming', In *Proceedings of the 10th International Conference on Textile Composites-TEXCOMP* (Vol. 10, pp. 271-279).
- [39] Sachs U and Akkerman R (2017), 'Viscoelastic bending model for continuous fiber-reinforced thermoplastic composites in melt', *Composites Part A: Applied Science and Manufacturing*, *100*, 333-341.
- [40] Ropers S, Kardos M and Osswald TA (2016), 'A thermo-viscoelastic approach for the characterization and modeling of the bending behavior of thermoplastic composites', *Composites Part A: Applied Science and Manufacturing*, *90*, 22-32.
- [41] Boisse P, Colmars J, Hamila N, Naouar N and Steer Q (2018), 'Bending and wrinkling of composite fiber preforms and prepregs. A review and new developments in the draping simulations', *Composites Part B: Engineering*, *141*, 234-249.
- [42] Wolthuizen DJ, Schuurman J and Akkerman R (2014), 'Forming limits of thermoplastic composites', In *Key Engineering Materials* (Vol. 611, pp. 407-414), Trans Tech Publications.
- [43] Sjölander J, Hallander P and Åkermo M. (2016), 'Forming induced wrinkling of composite laminates: A numerical study on wrinkling mechanisms', *Composites Part A: applied science and manufacturing*, *81*, 41-51.
- [44] Gutowski TG, Dillon G, Chey S and Li H (1995), 'Laminate wrinkling scaling laws for ideal composites', *Composites Manufacturing*, *6*(3-4), 123-134.
- [45] Boisse P, Colmars J, Hamila N, Naouar N and Steer Q (2018), 'Bending and wrinkling of composite fiber preforms and prepregs. A review and new developments in the draping simulations', *Composites Part B: Engineering*.
- [46] Haanappel SP (2013), *Forming of UD fibre reinforced thermoplastics*, PhD thesis University of Twente.
- [47] Haanappel SP, Ten Thije RHW, Sachs U, Rietman B and Akkerman R (2014), 'Formability analyses of uni-directional and textile reinforced thermoplastics', *Composites Part A: Applied science and manufacturing*, *56*, 80-92.