Towards Design for Thermoplastic Composites Manufacturing Using Process Simulation

R. Akkerman, B. Rietman, S. Haanappel, U. Sachs
ThermoPlastic composites Research Centre & University of Twente, Enschede, The Netherlands

Abstract

Robust and reliable process simulations can save significant costs during the detailed design phase by preventing major tool and product design modifications in the later product development phases. The essential material behaviour needs to be identified, modelled and characterised correctly to generate useful predictions of the process defects to be prevented. The dominant deformation mechanisms during forming and the relevant characterisation methods for fabric and unidirectional reinforced thermoplastics are discussed.
Development of an easily accessible database of material property data will facilitate the use of forming simulations in the detailed design phase of thermoplastic composite products, reducing their development times and improving the overall cost-effectiveness.

Keywords: Virtual Prototyping, Constitutive Models, Characterisation, Implementation

Introduction

Engineering design is recognised to be an iterative process. Ideally, conceptual design, embodiment design and detailed design are sequential phases of a generic product development process, followed by prototype manufacturing (requiring production planning and tool manufacturing) and testing (see Fig.1). However, it is well known that the real process is not that linear in time in most of the cases. Issues disregarded in earlier phases can lead to problems during detailing the original solution in a later stage. This may be corrected while detailing, but may also require modifications in the earlier phases with large impact on the whole design. Usually, the further in the development process, the more costly the modifications. In this sense, problems encountered during the production phase are likely to have the largest negative impact on the product development costs.

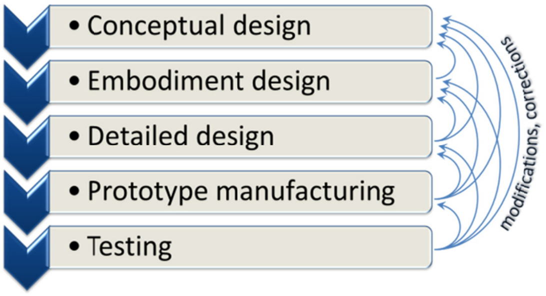

Fig.1 Engineering design phases in the product development process.

Clearly, the use of virtual tools can result in large cost savings by predicting production problems early in the design process. The savings increase with the investments required. Composite products are no exception to this general observation. Thermoplastic composites typically require higher machine and tooling costs than their thermoset counterparts. Process simulations for thermoplastic composites are hence important, if not essential, for competitive thermoplastic composite product development.

Obviously, these virtual tools must be accurate, fast and robust to be successful. The required input data must be easily accessible, the software must be user friendly and must have convenient interfaces with other software tools in the design chain. Logically, the software needs to match with the design phase where it is used: applications for conceptual design will differ from those for detailed design purposes in terms of requirements, level of detail and accuracy of the predictions.

Composites Forming Simulations

Press forming of thermoplastic composites has the potential of short cycle times required for mass production. As such, it is one of the candidate solutions for large scale application of composite materials in a range of industries. Typical production problems in this particular case concern process induced defects such as warpage, wrinkling and tearing. The occurrence of these defects is dependent on details such as tool radii, blank holders, blank shape, size and lay-up. Hence, predictive software with the purpose to prevent these defects can be used only in the detailed design phase, in which details of this kind will be defined.

A successful prediction of these defects first of all requires a sufficiently accurate description of the most relevant physical phenomena. In forming thermoplastic laminates, these are recognised as intra-ply shear, inter-ply shear/friction, tool/laminate friction and bending (schematically illustrated in Fig.2).

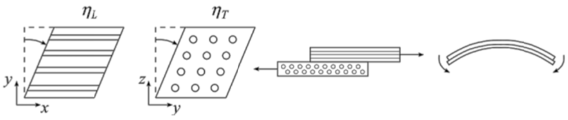

Fig.2 Deformation mechanisms in unidirectional fibre composites. From left to right: axial intra-ply shear, transverse intra-ply shear, inter-ply slip and bending.

The reinforcement structure has a large effect on these deformation mechanisms. Unidirectional plies will behave entirely different from fabric reinforced plies, and in turn very different from plies with discontinuous fibres. Also the interaction in a laminate between plies of different reinforcement appears to be strongly affected by the reinforcement structure. Here, we will restrict ourselves to continuous fibre plies.

Having established the nature of the relevant phenomena, these need to be described by an appropriate constitutive model. This in turn needs to be implemented correctly in the simulation software. To be of any use, it will then need material property data which must have been determined in a reliable and reproducible manner. It is very unlikely that forming simulation software will be widely applied without easily accessible material property data.

Intra-ply behaviour

The intra-ply behaviour of woven fabrics is dominated by a trellis-frame shear deformation. Large shear angles can be imposed with little effort (depending on the fabric constitution). Several methods are available to measure this shear response, e.g. the picture frame and the bias extension test (Fig.3).

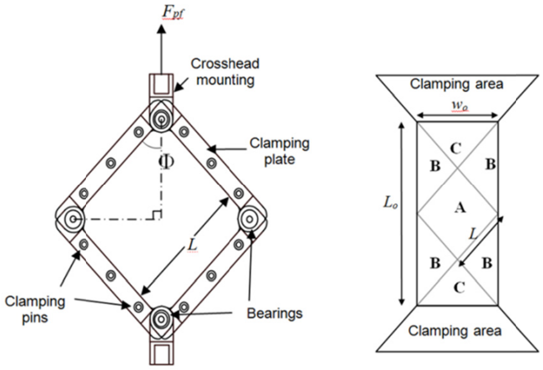

Fig.3 Picture frame (left) and bias extension (right) test.

Benchmark results [1] show that the measured responses have consistent trends, with reasonable quantitative agreement between different experimental set-ups, at least for dry fabrics. In addition to this, there is experimental evidence that fibre tensioning affects the apparent shear rigidity [2]. In this case there is no standardised test method, and only very little quantitative data available. Where most of the experimental work has been performed on dry fabrics at room temperature, the actual forming process is of course normally performed with impregnated laminates at high temperatures. Only few experimental set-ups have been used in these conditions and little quantitative data is available.

Unidirectional plies have an additional mode of deformation apart from in-plane shear, as there are no fibres to restrict extension normal to the fibre direction. However, the lack of reinforcement in the transverse direction makes unidirectional plies sensitive to damage (tearing), also at high temperature when the matrix is in a tough rubbery state. This complicates characterisation experiments at forming temperatures, as illustrated by a result of a preliminary shear testing on unidirectional carbon/PEEK (Fig.4).

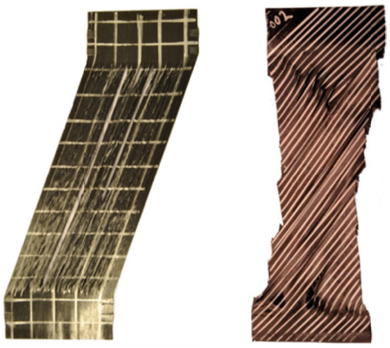

Fig.4 Result of a picture frame test (left) and a bias extension test (right) on unidirectional carbon/PEEK, respectively showing ply splitting and severe strain localisation.

A range of experimental set-ups have been proposed [3], resulting in a wide range of values for seemingly similar material properties related to the transverse behaviour of unidirectional plies. After critical evaluation of these methods, Haanappel et.al. [4] proposed a torsion experiment on rectangular bars in a rheometer, providing good thermal stability in an inert environment, as well as the accurate measurement of torque and twisting angle. With this set-up it was possible to characterise the intra-ply shear response as a function of temperature and deformation rate in terms of viscoelastic properties (storage and loss modulus versus frequency or time).

Only after having characterised the material at hand, it is possible to select or develop an appropriate constitutive model to be used in the forming simulations. As a minimum, this constitutive model needs to take into account the anisotropy induced by the fibrous reinforcement, as the stiffnesses of fibres and matrix differ many orders of magnitude. The composite material during forming can be interpreted or as a system composed of several discrete fractions (e.g. fibres and matrix) or as a single continuum. Elastic, viscous, viscoelastic and plastic types of descriptions have been used to this end. The resulting constitutive equation will be an addition of terms (connected in series or parallel) related to the separate constituents and the reinforcement structure [5].

The framework for continuum type constitutive equations of fibre reinforced materials ([6], [7]) is based on continuum mechanics arguments. Needless to say, this continuum approach disregards detailed micromechanics, e.g. related to bending, shear, extension, buckling and compaction of the tows as observed in dry fabric deformations ([8], [9]). Additional elastic, visco-elastic (linear or non-linear) and plastic effects require more complex equations, in general requiring more material property data.

Inter-ply behaviour

The motion of plies with respect to each other and with respect to tool surfaces is restricted by friction. This friction can be explained as a composite response due to the interaction of fibres, matrix and counter surface. Limited experimental work shows evidence that the friction depends on temperature, pressure and sliding velocity. One of the simplest perceptions is that of a resin rich layer of arbitrary thickness h acting as a lubricant. Considering the matrix as a viscous fluid (possibly shear thinning) leads to a simple formulation for inter-ply slip,

$$\tau = \eta\left(\dot{\gamma}, T, p\right) \cdot \dot{\gamma}, \qquad \text{with} \quad \dot{\gamma} = \frac{U}{h}, \tag{1}$$

where τ is the shear stress, η the resin viscosity, $\dot{\gamma}$ the shear rate, T the temperature, p the pressure and U the relative velocity between the two surfaces. This description would imply that the friction does not depend on pressure. Alternatively, a Coulomb approximation can be assumed, more applicable to friction between two solids,

$$\tau = \mu \cdot p \tag{2}$$

where the dynamic coefficient of friction μ would usually not depend on pressure and sliding velocity.

The characterization of ply-ply and tool-ply friction of thermoplastic composites at forming temperatures requires a dedicated set-up. Only few test set-ups have been reported in literature, some using a pull-through and some using a pull-out principle. Ten Thije developed a pull-through set-up which is suited for routine friction measurements requiring little time per experiment [10].

Extensive testing and analysis by ten Thije et al [11] on woven fabric reinforced thermoplastics indicated that the dependency of the friction on velocity and pressure can be explained from a meso-mechanical perspective. Evaluating the hydrodynamic forces between the fabric structure and the counter surface leads to the same trends and the same magnitude of shear forces as observed experimentally (Fig.5).

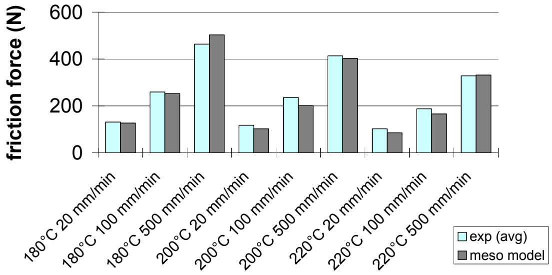

Fig.5 Tool/ply friction forces on glass/PP laminates: experimental results vs. model predictions [12].

This mesoscopic model is able to predict the macroscopic response (i.e. the coefficient of friction and the film thickness) with only the fabric structure, the resin viscosity relation and the macroscopic pressure, temperature and sliding velocity as input. In this case the macroscopic response can be simplified subsequently to a Stribeck relation, giving the coefficient of friction μ as a function of the Hersey number $He = \eta U/p$.

Regrettably, this simple mesoscopic approach does not apply to unidirectional plies. This fibre structure does not generate the hydrodynamic forces necessary to generate a resin film leading to essentially hydrodynamic lubrication. Our current hypothesis is one of mixed lubrication, where fibre-fibre contact and hydrodynamic interaction in between lead to the overall tool-ply friction as observed in experiments.

Bending

Very limited experimental data is available in literature on the flexural response of thermoplastic composites in forming conditions. The laminate response will be somewhere in between Kirchhoff bending and transverse shear (Fig.6).

Fig.6 Kirchhoff bending (left), with intra ply shear (middle) and a combination with inter-ply shear (right).

A novel set-up was developed recently, based on the KES set-up for flexural rigidity and implemented as a rheometer fixture (Fig.7).

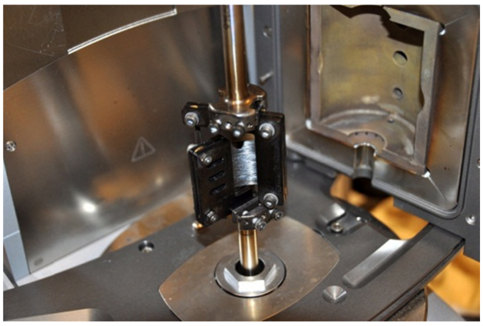

Fig.7 Composite bending test set-up within a standard rheometer.

The preliminary results show the appropriate smooth deformations and good reproducibility. The test method has large potential for standardised characterisation of the flexural behaviour.

Implementation

An accurate numerical solution has to be able to cope with the extremely high anisotropy encountered in thermoplastic forming processes, in combination with the large non-orthogonal deformations due to the ease of intra-ply shearing. Here we employ a dedicated implicit FE formulation as presented in [13] and implemented in the AniForm software. The constitutive models for intra-ply response, inter-ply and tool-ply friction, as well as laminate bending have been selected in accordance with the experimentally observed responses. In parallel, TPRC is working on setting up and populating a material database to provide the necessary input data for the relevant thermoplastic composite materials, using the characterisation tools as described.

Application and Results

The methods outlined above are critically evaluated and benchmarked against results of press forming experiments. An example of this validation was presented in [14]. A stiffener rib was press formed with various thermoplastic laminates with a quasi-isotropic lay-up of woven or unidirectional, glass or carbon fibres embedded in different thermoplastic resins (Fig.8).

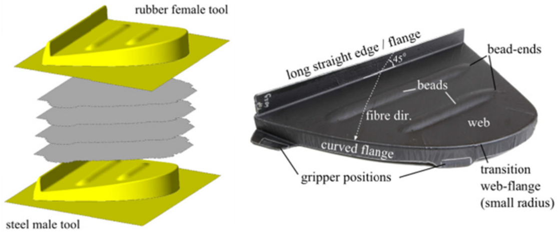

Fig.8 Validation of composites forming simulations [14].

Characterisation of the different materials leads to different sets of material property data which are then input to the composites forming simulations. Wrinkles were predicted in the correct critical areas, and the predicted strain fields compared well with the experimental data. Qualitatively good agreement was found. Sensitivity studies are currently underway to improve on the quantitative results.

Conclusion

Simulations of composites forming simulations require the right constitutive models, fed with the correct material property data and implemented in a stable and accurate numerical scheme. Good progress has been made in the recent years with the required characterisation methods, opening the possibilities to develop an easily accessible database of material property data. Provided the simulation software fits well in the design chain, it is to be expected that these simulations will find good use in the detailed design phase of thermoplastic composite products. Product development times can be reduced, improving the overall cost-effectiveness.

Acknowledgements

The Thermoplastic Composite Research Centre (TPRC) is supported by the Region Twente and the Gelderland & Overijssel team, by means of the GO Programme EFRO 2007-2013, which is gratefully acknowledged.

References

[1] J. Cao, R. Akkerman. P. Boisse et al, Comp.A 39 (2008), 1037-1053.
[2] P. Harrison, F. Abdiwi, Z. Guo, P. Potluri, W.R. Yu, Comp.A 43 (2012), 903-914.
[3] P. Harrison, M.J. Clifford, In A.C. Long (ed), Design and manufacture of textile composites, Woodhead, 2005.
[4] S.P. Haanappel, R.H.W. ten Thije, A.D. Rietman, R. Akkerman, Proc. Esaform 2011, Belfast, Ireland.
[5] S.W. Hsiao, N. Kikuchi, Comp. Meth. in Appl. Mech. Eng. 177 (1999), 1-34.
[6] T.G. Rogers, Composites, 20 (1989), 21-27.
[7] A.J.M. Spencer, Comp.A, 31 (2000), 1311-1321.
[8] S.V. Lomov, Tz. Stoilova and I. Verpoest, Proc. Esaform 2004, Trondheim, Norway, 345-348.
[9] G. Hivet and P. Boisse, Proc. Esaform 2006, Glasgow, United Kingdom, 787-790.
[10] R.H.W. ten Thije, R. Akkerman, Int.J. of Mat. Forming 2, suppl.1 (2010), 197-200.
[11] R.H.W. ten Thije, R. Akkerman, M. Ubbink, L. van der Meer, Comp.A 42 (2011), 950-960.
[12] R. Akkerman, M.P. Ubbink, M.B. de Rooij and R.H.W. ten Thije, Proc. Esaform 2007, Zaragosa, Spain.
[13] R.H.W. ten Thije, R. Akkerman and J. Huétink, Comp. Meth. in Appl. Mech. Eng. 196 (2007), 3141-3150.
[14] S.P. Haanappel, U. Sachs, R.H.W. ten Thije, B. Rietman, and R. Akkerman, Key Eng. Mat. 504-506 (2012), 237-242.