
Simplified and advanced simulation methods for prediction of fabric draping

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ABSTRACT. Three principle methods are available for fabric draping analysis; namely, simplified “mapping” and Finite Element methods applied at the macro- and meso- levels. The mapping method was first introduced in the 1950’s and due to its simplicity is still the preferred technique for industrial work. During the past decade Finite Element methods have evolved that offer significant improvements in terms of accuracy and range of application. This method can allow definition of the forming system, friction and permit material laws valid for a wide range of fabric types. Two levels of fabric modelling are possible; first, macro-models which approximate the fabric as a homogeneous continuum and, second, more complex meso- models that accurately represent fabric architecture and thereby the complex deformation mechanisms. This paper gives an overview of these techniques, their limitations and the state-of-the-art.

KEYWORDS: draping analysis, composites forming, fabric mechanisms, woven fabrics, non crimp fabrics.

1. Introduction

Prediction of fabric draping is an important step in the virtual design of composites. The draping analysis should, ideally, give reliable information on changes in the fabric architecture such as tow and thickness redistribution, compaction and also identify drapeability limits such as fabric buckling, shear locking and regions of excessive deformation. Prediction of these defects allows the designer to consider alternative draping processes, fabric restraints or fabric types. Information on fibre reorientation is, for example, required for accurate stiffness analysis of a structural composite part. It is also important information for failure prediction and determination of orthotropic permeability models for impregnation analysis in Liquid Composite Moulding. However, it should be noted that both these latter topics are areas of active research and reliable predictive models have yet to be developed.

Methods for draping analysis can be broadly grouped into three categories: First, are the original kinematic methods which essentially use mapping techniques to try and fit a flat fabric to the desired geometric shape. These “mapping” methods are fast, robust and require only minimal data input to describe the geometry and initial fibre directions. The second and third groups are both based on Finite Element (FE) techniques and differ in the level of detail used to model the textile fabric; in each case the generality of the FE method allows accurate representation of the tooling (matched metal, membrane, etc.), tool-to-ply friction and other process variables such as heat.

The second group uses macro- FE methods to approximately represent the fabric as a homogeneous material using computationally efficient constitutive laws and continuum Finite Elements. The inherent limitation is that the fabric is not really a continuum, but can be more closely likened to a structure comprising of discrete tows, possibly intertwined, or loosely held together with stitching. Interaction of the tows via contact, with friction, and deformation of the stitching control the complex deformations of the fabric. This leads to the third group which attempts to accurately represent the structural features of the fabric using FE techniques and meso-mechanical modelling methods and thus capture the true deformation mechanisms. Whereas the macro- FE technique can be considered industrial and several commercial FE codes have been applied to fabric draping (PAM-FORM; ABAQUS), the latter meso- modelling methods are at the research stage and realistic, computationally efficient methods, still have to be developed (Creech *et al.*, 2003; ten Thije *et al.*, 2003). This paper presents an overview of the three methods outlined above.

2. Fabric deformation mechanisms

Ideally textile fabrics should be drapeable and provide good final mechanical properties in the impregnated composite. Examples include, amongst others, variations of woven fabrics (plain, twill and satin) and, as shown in Figure 1, unidirectional (UD) and a biaxial Non Crimp Fabrics (NCF).

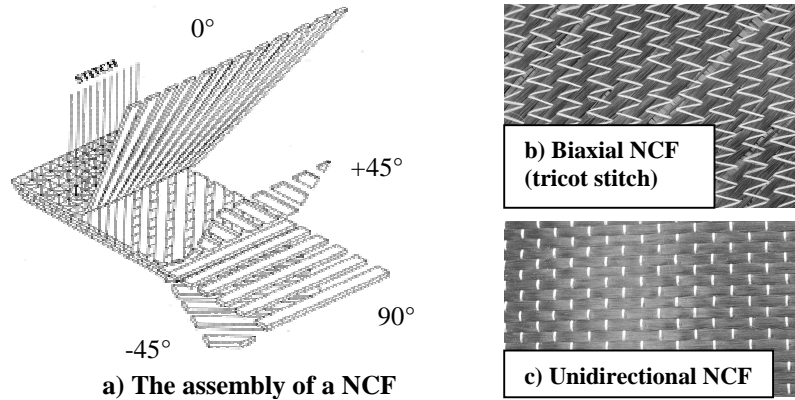


Figure 1. Example of two popular drapeable NCF's for structural composites

Fabrics undergo preferential deformation mechanisms which are controlled by their architecture and Figure 2 shows schematically the predominant deformation modes for most fabrics. Usually inter-fibre shear, or the 'trellis' mode, offers least resistance to deformation and, consequently, fabrics adapt their shape primarily by shearing mechanisms; the type of weave (plain, twill, etc), or the type of stitch in a NCF will determine the fabric shear resistance. The presence of additional tows in triaxial fabrics essentially prevents fabric shearing. Inter-fibre sliding is a secondary mode of deformation occurring at higher shear angles and is more prevalent in NCF materials for which the lack of tow interlocking results in less constraint of fibre cross-over positions. Other minor deformation modes are also possible, including fibre buckling in compression or fibre straightening in tension.

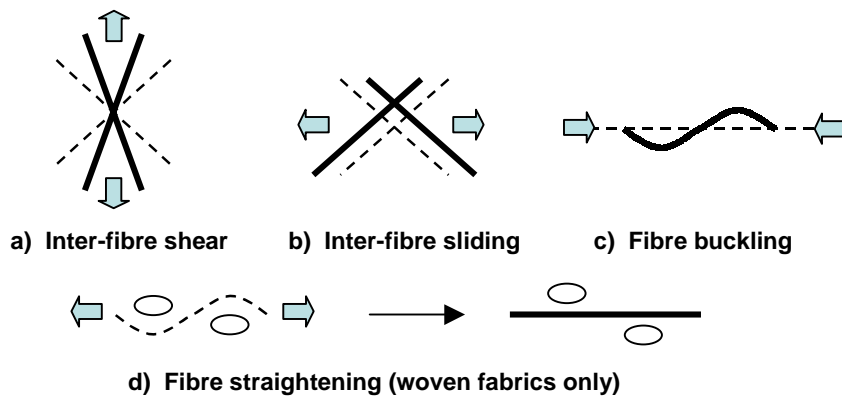


Figure 2. Examples of the principle deformations modes for drapeable fabrics

3. Experimental techniques

Currently there are no standards regarding the shear testing of unidirectional or biaxial engineering fabrics. However, two testing methods commonly used are the picture frame and bias extension tests, as shown in Figure 3. The picture frame test, Figure 3a, confines the fabric to pure shear and provides both shear force data and the inter-fibre ‘locking’ angle. This locking is usually defined at the onset of buckling (wrinkling) and fabrics can often reach up to 70° shear before this occurs. A more simple technique is the bias extension test which involves simple extension of a coupon of material with a $\pm 45^\circ$ fibre angle. Although more simple in execution, the force data obtained is complicated by the inhomogeneous state of shear within the specimen, as shown in Figure 3b. However, this test proves useful in observing the occurrence of shear-bias and the prevalence of inter-fibre sliding, especially within NCF materials. It is a current topic of work to normalise both the picture frame (Peng *et al.*, 2004) and the bias extension (Harrison *et al.*, 2004) tests. Additional testing for mechanical data to be used in FE codes includes; characterisation of inter-ply friction, flexural stiffness (ASTM D1388-96^{E1}) and, specific to woven fabrics, a biaxial tensile testing device can be used to characterise the influence of yarn undulation in producing non-linear tow deformation (Boisse *et al.*, 1997).

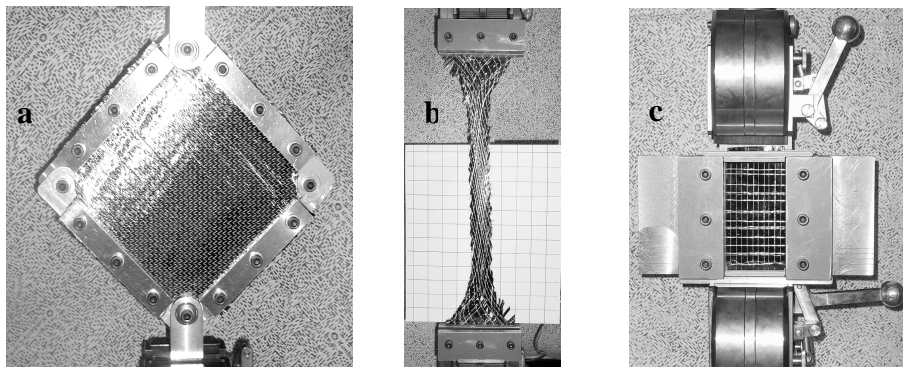


Figure 3. The main fabric characterisation tests; a) the picture frame; b) the bias extension, and; c) pull-out tests

For NCF's the through-thickness stitching controls relative sliding of tows and information on the resistance to movement is required in some numerical models to be presented. This stitch force-displacement relationship can be found from a pull-out test in which a group of tows from one ply are extracted from adjacent plies (Creech *et al.*, 2003; ten Thije *et al.*, 2003), Figure 3c.

4. Kinematic analysis methods

Numerical analysis of fabric forming has, until recently, been dominated by methods based on geometric mapping techniques (commonly called “kinematic”, “fish-net”, “mapping” or “pin-jointed net” methods). These techniques are based on a simple kinematic algorithm in which the fabric is idealised as an orthogonal network of fibres with cross over points acting as fixed pin-jointed nodes. The basis of this algorithm was developed in the 1950’s by Mack and Taylor (Mack *et al.*, 1956) and generally makes the following assumptions about the fabric (Rudd *et al.*, 1997):

- Fibre crossovers act as pin-joints, *i.e.* there is no relative slip;
- Fibre segments are straight between pin-joints;
- Fibre segments are inextensible;
- Uniform surface contact is achieved;
- Fabric layers are infinitely thin.

In order to generate a deformed fibre pattern the method requires the two initial fibre directions (L_1, L_2) of the “net”, the edge length of the net segments (a, b) and a single starting point (P) to be specified as shown in Figure 4. Working outward from this starting point the draped fibre paths can be found by solving the intersection of each pin-joint node, Equations [1], and enforcing that this point lies on the geometry surface given by Equation [2],

$$\begin{aligned} (x_{i,j} - x_{i-1,j})^2 + (y_{i,j} - y_{i-1,j})^2 + (z_{i,j} - z_{i-1,j})^2 &= a_i^2 \\ (x_{i,j} - x_{i,j-1})^2 + (y_{i,j} - y_{i,j-1})^2 + (z_{i,j} - z_{i,j-1})^2 &= b_j^2 \end{aligned} \quad [1]$$

The surface geometry required to be analysed is,

$$f(x, y, z) = 0. \quad [2]$$

As the above equations suggest, the method can be idealised as the intersection of the required geometry surface with two spheres of radius a and b , centred at points $(i-1, j)$ and $(i, j-1)$. This intersection can be solved explicitly if the required geometry is defined by a geometrical function, such as a hemisphere of known radius, or numerically when an arbitrary surface has to be fitted.

The assumptions and solution scheme of kinematic methods clearly oversimplify the true fabric with only pure in-plane shear being effectively simulated. Strictly, this should limit its application to balanced woven fabrics, although it has been applied, with varying success to numerous dry and impregnated fabrics (Bergsma, 1993; Trochu *et al.*, 1996). In addition, the standard method permits no consideration of the physics of the forming process and is also highly dependant on the initial choice of starting point and fibre directions. For many geometries this

position is obvious, for example the highest point of a hemisphere, but more complex geometries may have multiple initial (or early) contact points rendering the choice of any, almost certainly, incorrect.

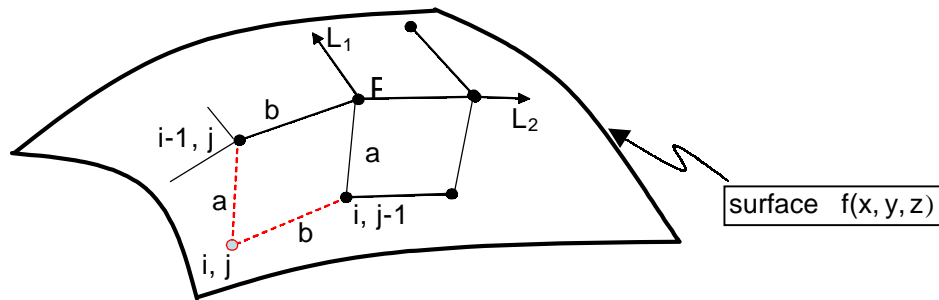


Figure 4. The solution scheme of a kinematic drape algorithm

Much research has attempted to improve limitations of the kinematic methods and work has focussed either on techniques to treat arbitrary geometries and multiple contact points (Van West *et al.*, 1990; Long *et al.*, 1994), or improve the fabric model allowing a broader range of fabric types to be treated. Improvements to the fabric model have largely been motivated by the current high interest in advanced textiles such as NCF's. Long (Long, 2001) has introduced a non-symmetric shear model for NCF's to account for their non-symmetric behaviour due to the stitching style and its orientation relative to the tows. Shear energy data is obtained from picture frame testing for both positive and negative shear and used in an iterative energy minimisation scheme to determine a deformed "net" representing the minimum deformation energy. Further advances have been proposed for UD NCF material (de Luca *et al.*, 2002) in which fibre slippage is a more prevalent deformation mechanism. In this case the kinematic algorithm does not allow extension in the fibre direction, but permits controlled extension in the transverse directions.

Figure 5 shows the application of the technique to the rear seat bench and wheel arches of an automotive structure. In this study the commercial QUIK-FORM code (QUIK-FORM) has been used with conventional techniques requiring the selection of a starting point and initial fibre directions and assuming that the standard method using Equations [1] and [2] are reasonably valid for bi-axial NCF. This general code uses a FE mesh to describe the arbitrary geometry to be mapped, Figure 5a. The fabric is then mapped from the selected starting point, Figure 5b, and contours of shear angle are produced, Figure 5c. It is evident from this contour that shear angles of 88° are predicted which is clearly impossible for NCF; never-the-less, zones where excessive shear and fabric buckling will occur can be identified.

These kinematic methods are fast, reasonably robust and require only minimal data input and a geometric description of the shape to be formed. The limitation of the method is that it does not represent any physics of the forming process and details such as fabric deformation law, tool-to-fabric friction and blank-holder restraints cannot be modelled. Despite this, mapping methods are popular as a quick design tool and a number of commercial codes are available (QUICK-FORM; CATIA CPD; MSC Laminate Modeller; FiberSIM). In general, the Finite Element technique offers the possibility to overcome many of these limitations and will be discussed in the remainder of this paper.

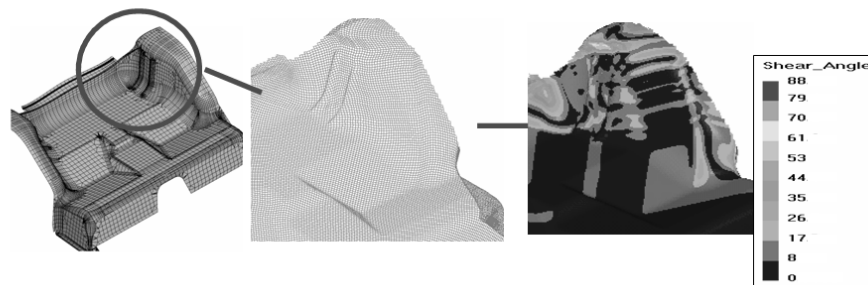


Figure 5. Example kinematic drape simulation results (TECABS, 1998)

5. Finite element modelling techniques for draping analysis

Two classes of Finite Element methods are available, either the Implicit or Explicit method. The former, Implicit method, is more widely available and used for a broad range of problems including static stress analysis. The Explicit method has received increasing attention during the past two decades, particularly for dynamic, highly nonlinear, contact dominated problems; car crash and metal stamping simulation are applications particularly well suited to this technique. Briefly, both techniques use conventional Finite Elements to discretise and represent the structure. The Implicit method assembles the global stiffness matrix $[K]$ which is used to determine resulting nodal displacements $\{u\}$ from applied nodal forces $\{P\}$,

$$\{P\} = [K] \{u\} \text{ or by inversion, } \{u\} = [K]^{-1} \{P\}. \quad [3]$$

From nodal displacements the element stresses and strains are computed. Problems involving contact, buckling and material nonlinearity yield a nonlinear stiffness matrix $[K]$ which requires a CPU intensive iterative solution. The alternative Explicit algorithm uses a different solution strategy and poses the problem as a dynamic one, using the linearised equations of motion,

$$[M]\{\ddot{u}\}_n + [K]\{u\}_n = \{P\}_n, \quad [4]$$

where $\{u\}$ and $\{\ddot{u}\}$ are vectors of nodal displacement and acceleration, n is the cycle number at time T_n (after $n\Delta T$ time steps); $[M]$ and $[K]$ are the Mass and Stiffness matrices respectively. A central finite difference solution is used to update nodal displacements from which element stresses and strains at each timestep are computed. The method is 'conditionally stable' through use of an integration time step ΔT below a critical value, dependant on the smallest element size and material properties.

A comparison of the two methods is given (Cook *et al.*, 1989); briefly, the Implicit method is superior for static, mildly nonlinear problems; whereas the Explicit method is advantageous for medium to high velocity dynamic problems involving large scale deformation and material nonlinearity. Also, it is straightforward to treat sheet buckling and contact between bodies using the dynamic integration scheme, both of which are important in draping analysis.

5.1. Macro-mechanical finite element modelling of fabrics

This section describes the theory and application of the Explicit FE method to draping simulation of Fabrics using a macro- approach. Much of the initial research and development work presented was undertaken within a CEC funded Brite-Euram project (BE-5092) which led to the first commercial FE code (PAM-FORM; Pickett *et al.*, 1996) dedicated to thermoforming simulation of advanced fibre reinforced thermoplastics. This project resulted in validated techniques for modelling the viscous interface between plies and new constitutive laws to characterise each ply. An important result of this work was the development of new techniques to correctly model the deformation of a stack of plies in a composite laminate. This must represent ply-stretching, intra-ply shearing of individual plies and inter-ply shearing between plies. These mechanisms can only be represented if each ply is separately discretised using, for example, shell elements and relative sliding between plies is modelled using an appropriate friction law.

Figure 6 shows the main features and constitutive laws used for a stack of plies. Parameters for the inter-ply viscous-Coulomb friction law, Equation [5], must be determined from experimental testing as briefly described in section 3. The sliding resistance forces depend on the summation of dry friction $\mu\Delta P$ and viscous friction $\eta_T \Delta Vel$, where η_T is the resin viscosity, μ is the Coulomb friction, ΔP is the pressure difference between plies and ΔVel is the relative sliding velocity between plies. For the ply an elastic fibres embedded in a viscous resin law (Ó Brádaigh *et al.*, 1993) is assumed, Equation [6]. The first part of this equation is the elastic fibre contribution, whereas the second part is the rate dependant viscous resin contribution. Both resin longitudinal (parallel to fibres) viscosity (η_L) and transverse viscosity (η_T) are included which may be either constant in iso-thermal forming, or temperature dependant in thermoforming.

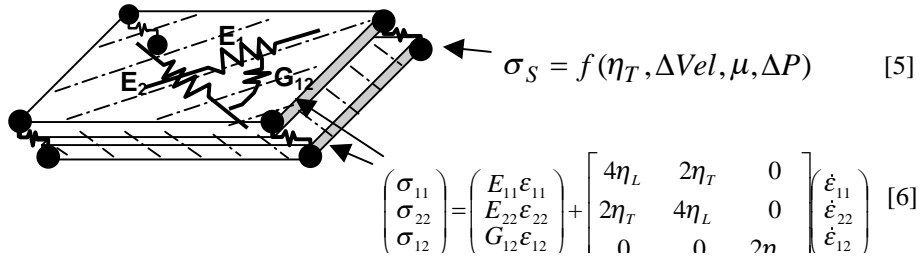


Figure 6. Two stacked plies and the constitutive laws for composite sheet forming

The flexibility of the Finite Element method allows most variables found in sheet composite forming to be represented. For thermoforming a temperature analysis is undertaken and results coupled to the constitutive laws. In the case of dry fabrics, the viscous part of the constitutive law may be ignored. Both UD and woven fabrics can be defined in the ply material model using, respectively, either a constant elastic or non-linear elastic model. The non-linear model is intended to approximate stiffness variations in woven fabrics due to tow undulations. However there is no account for the coupling of warp and weft tow tensions as considered by (Boisse *et al.*, 1997).

The idealisation to represent a biaxial NCF is adapted from Figure 6 and shown in Figure 7. Two plies representing the two fabric layers ($\pm 45^\circ$) are modelled with shell elements and a simple unidirectional stiffness law. The stitching which tie these shells together is modelled using spring elements. Parameters for the in-plane moduli, E_1 and E_2 , can be estimated, or determined *via* coupon testing. The ‘picture frame’ test is an effective means to obtain the intra-ply shear G_{12} and the shear locking angle. In the constitutive model this locking is imposed by rapidly increasing shear modulus once the experimentally observed locking angle is reached. Dry friction and stitch force-displacement data are also obtained using the simple test methods briefly mentioned in section 3.

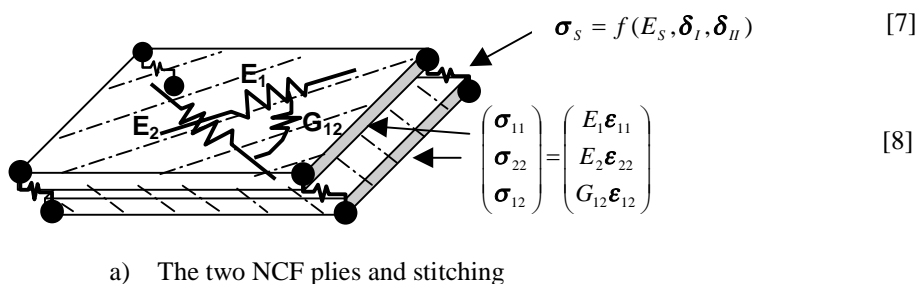
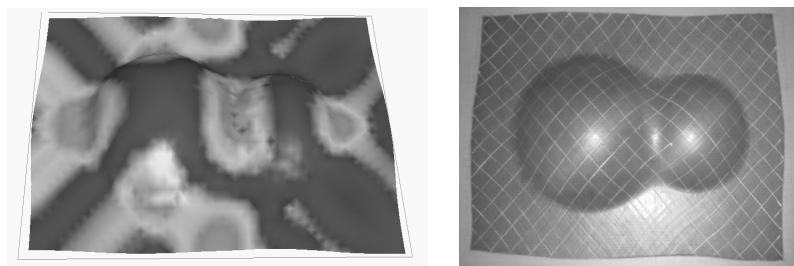
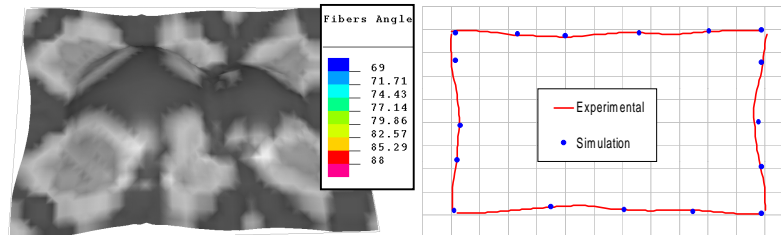


Figure 7. Two stacked plies and the constitutive laws for NCF

Simulation of the bias extension, picture frame, bending rigidity and pull-out tests can be used to calibrate input ply and stitch properties. The friction test is used to calibrate the friction models. In order to validate the model experimental draping tests of NCF have been conducted over a double hemisphere mould with vacuum rubber membrane forming equipment. Figure 8 shows example test and simulation results for two configurations using a $\pm 45^\circ$ and a $0^\circ/90^\circ$ chain stitched NCF (430gm^2 carbon fabric from Saertex). This work has shown a good agreement for both fabric shear deformations and distortion of the periphery of the fabric.



a) Simulation and test result comparison for the $\pm 45^\circ$ NCF



b) Simulation and test results for the $0/90^\circ$ NCF

Figure 8. Experimental and simulation results for membrane forming a biaxial NCF sheet: a) $\pm 45^\circ$ fabric orientation and b) $0-90^\circ$ fabric orientation

5.2. Meso-mechanical finite element modelling of fabrics

For a truly accurate representation of fabric deformation it will be necessary to employ meso-mechanical modelling methods. This work is an active area of research and cannot yet be considered industrial. This section briefly presents some work attempting to develop meso-mechanical Finite Element models for Non Crimp Fabrics. The exciting opportunity of this approach is that accurate information for subsequent stiffness, failure and impregnation analysis of composites will be available. For NCF it has been identified (Wiggers *et al.*, 2003) that there are five main mesoscopic deformation mechanisms, these are:

- Tow Compaction;
- Inter-tow frictional sliding;
- Stitch tension;
- Frictional sliding of stitching threads;
- Interaction between the fibre tows and stitching.

Figure 9 shows these deformation mechanisms for a bias extension test of a $\pm 45^\circ$ coupon of NCF (a chain stitched 430gm^{-2} carbon fabric from Saertex) with initial undeformed size 100mm wide by 250mm long. This test generates three distinct deformation zones due to the constraints induced by the grips; only the centre region has a state of pure fabric shear. This pure shear region can be approximately represented using the previous macro-FE techniques, however, the tow slippage and stitch tearing mechanisms, which will also occur in practical problems requiring large fabric deformations, cannot be treated.

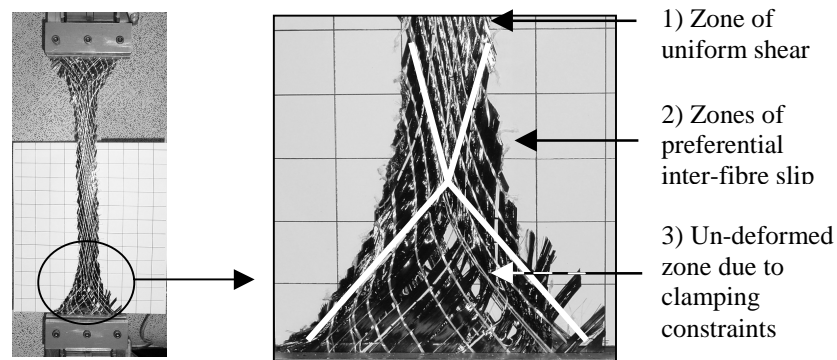


Figure 9. Fabric deformation during bias extension testing of a biaxial $\pm 45^\circ$ NCF

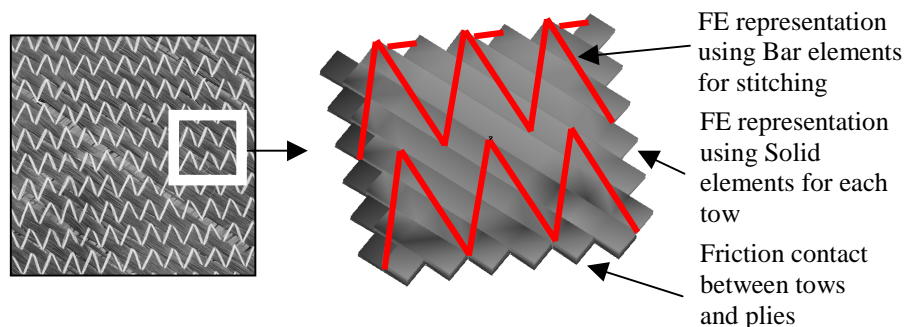


Figure 10. A 'representative cell' of the meso-mechanical model for NCF

A 'representative cell' of a meso-mechanical model for NCF is shown in Figure 10, based upon a 320gm^{-2} tricot stitched fabric from Saertex. This model comprises of two fibre layers, constructed of solid elements to represent the tows and through thickness stitching, using bar elements, to represent the tricot stitch. Friction contact is defined between the tows and the plies. This model uses the coarsest possible modelling methods so that analysis of relatively large models should be possible with currently available computing power.

Each tow of the model is represented by a row of solid elements to which a heterogeneous unidirectional composite bi-phase model (PAM-CRASH) is assigned, Figure 11a. The tow properties are defined through the inextensible fibre contribution and matrix properties which approximate internal friction, shear and fibre compaction behaviour. The matrix parameters are defined through a low elastic modulus, low shear modulus and Poisson ratio in each of the three orthotropic axes. In order to simulate shear 'locking', as a close packed fibre distribution is approached, an internal contact algorithm is used to prevent excessive transverse element deformation.

The stitching, Figure 11b, is represented by bar elements having a non-linear elastic, tension only formulation in the tricot geometry. Inter-tow contact is simulated through application of a contact algorithm between the solid elements of adjacent tows and plies and, finally, frictional forces are applied during inter-tow slip using a simple Coulomb friction law. Currently the model uses 'soft' elastic mechanical data to approximate the resistance of the stitching on fabric deformation; all bar elements are interconnected with coincident nodes. However, this method does not permit complete inter-stitch frictional sliding to be simulated.

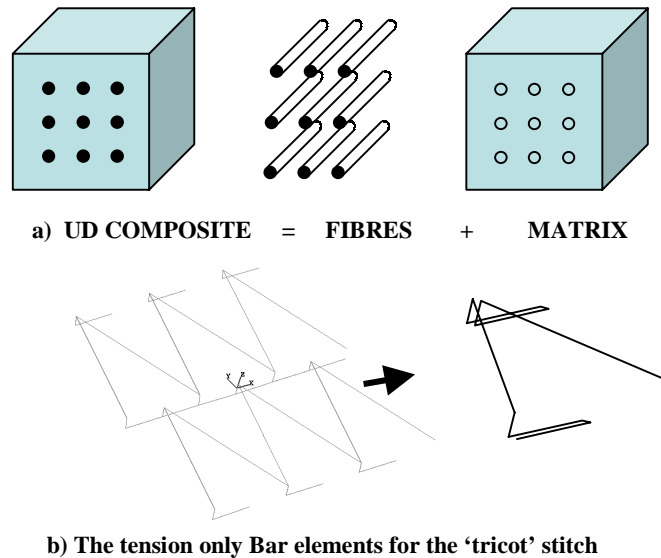


Figure 11. Component elements of the meso-mechanical model for NCF

Simulation results for a bi-axial NCF are shown in Figure 12. As can be see from this figure the meso-mechanical model is able to represent the three key deformation zones that were identified from the test specimen in Figure 9. Pure shear occurs in zone 1 which, combined with the area of un-deformed tows in zone 3, causes preferential inter-tow slippage and tow-buckling in zone 2.

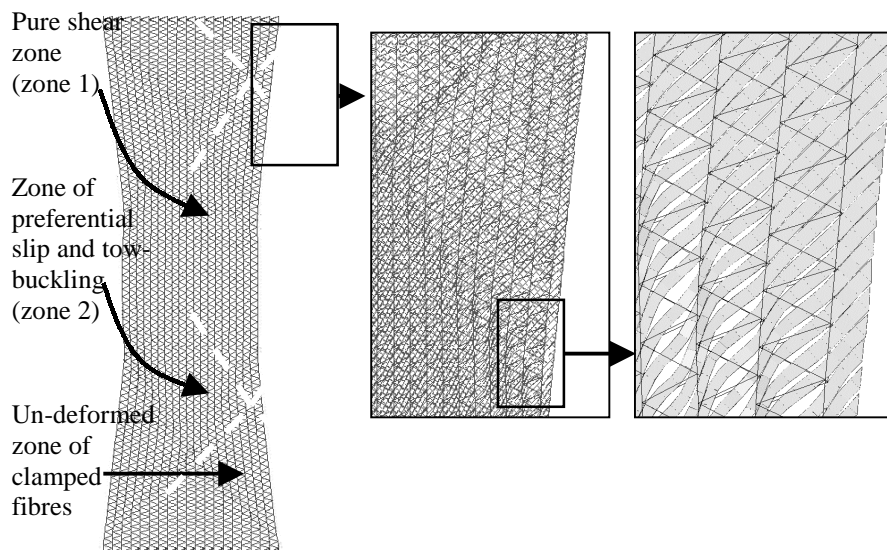


Figure 12. Simulation result of a bias extension simulation at 20% strain

6. Conclusion

An overview of simple kinematic and more sophisticated FE methods for preforming simulation of fabrics has been given. The original kinematic method provides a robust and straightforward technique, but neglects important process parameters and is strictly only valid for certain balanced woven fabrics; nevertheless, in the hands of a cautious designer it is a valuable and informative design tool. More sophisticated FE techniques offer greater accuracy and enable a wide range of forming processes and fabric types to be considered, but do require considerably greater expertise from the analyst and computer power. However, only this approach offers the opportunity to properly represent the physics of the forming process and thus allow optimisation of the process. A brief introduction to ongoing research to develop meso-mechanical models for advanced fabrics has been given; this technique could accurately model the fabric and its deformation, and provide important data for subsequent stiffness, failure and impregnation analysis.

Acknowledgements

The authors wish to gratefully thank ESI Software (France) for supply of software and EPSRC (UK) for their financial support. Thanks are also due to the Composites group at the University of Twente (Netherlands) for supply of the double hemisphere mould used for some of the draping work.

7. References

- ABAQUS, *ABAQUS Europe BV*, Gaetano Martinolaan 95, 6201 BP Maastricht, Netherlands.
- ASTM D1388-96^{E1}, *Standard Test for Stiffness of Fabrics*.
- Bergsma O.K., "Computer Simulation of 3D Forming Processes of Fabric Reinforced Plastics", *Proceedings of the 9th International Conference on Composite Materials*, Madrid, Spain, 1993, pp. 560-567.
- BE-5092., Brite-Euram Project, Industrial Press Forming of Continuous Fibre Reinforced Thermoplastic Sheets and the Development of Numerical Simulation Tools, 1992-1996.
- Boisse P., Borr M., Buet K., Cherouat A., "Finite Element Simulations of Textile Composite Forming Including the Biaxial Fabric Behaviour", *Composites: Part B*, Vol. 28B, 1997, pp. 453-464.
- CATIA CPD Draping Module, *Composites Part Design, Producibility Analysis Module*, Dassault Systèmes, 9 Quai Marcel Dassault, 92150 Suresnes, France.
- Cook R.D., Malkus D.S., Plesha M.E., *Concepts and Applications of Finite Element Analysis*, 1989, Wiley Publishing.
- Creech G., Pickett A.K., Greve L., "Finite Element Modelling of Non Crimp Fabrics for Draping Simulation", *The 6th International ESAFORM Conference on Material Forming*, Salerno, Italy, 2003, pp. 863-866.
- de Luca P., Pickett A.K., Morisot O., "Coupled Pre-Forming/Injection Simulation of Liquid Composite Moulding Processes", *SAMPE*, Long Beach, USA, 2002, pp. 1307-1316.
- FiberSIM, *VISTAGY Inc.*, 486 Totten Pond Road, Waltham, MA 02451-1917, USA.
- Harrison P., Clifford M.J., Long A.C., "Shear Characterisation of Viscous Woven Textile Composites: a Comparison Between Picture Frame and Bias Extension Experiments", *Composite Science and Technology*, Vol. 64, 2004, pp. 1453-1465.
- Long A.C., "An Iterative Draping Simulation Based on Fabric Mechanics", *4th International ESAFORM Conference on Material Forming*, Liege, France, 2001, pp. 99-102.
- Long A.C., Rudd C.D., "Simulation of Reinforcement Deformation During the Production of Preforms for Liquid Moulding Processes", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 208, 1994, pp. 269-278.
- Mack C., Taylor H.M., "The Fitting of Woven Cloth to Surfaces", *Journal of the Textile Institute*, Vol. 47, No. 8, 1956, pp. 477-488.
- MSC Laminate Modeller, *MSC. Software Corporation*, 2 MacArthur Place, Santa Ana, CA 92707, USA.

- Ó Brádaigh C.M., McGuinness G.B., Pipes R.B., "Numerical Analysis of Stresses and Deformations in Composite Materials Sheet Forming: Central Indentation of a Circular Sheet", *Composites Manufacturing*, Vol. 4, No. 2, 1993, pp. 67-83.
- PAM-CRASH Solver Notes Manual, *ESI Group*, 99 Rue des Solets, Silic 112, 94513 Rungis-cedex, France.
- PAM-FORM, *ESI Group*, 99 Rue des Solets, Silic 112, 94513 Rungis-Cedex, France.
- Peng X.Q., Cao J., Chen J., Xue P., Lussier D.S., Liu L., "Experimental and Numerical Analysis on Normalization of Picture Frame Tests for Composite Materials", *Composite Science and Technology*, Vol. 64, 2004, pp. 11-21.
- Pickett A.K., Cunningham J.E., deLuca P., Johnson A.F., Lefebure P., Mallon P., Sunderland P., Ó Brádaigh C.M., Vodermeier A., Werner W., "Numerical Techniques for the Pre-Heating and Forming Simulation of Continuous Fibre Reinforced Thermoplastics", *SAMPE*, Basel, Switzerland, 1996.
- QUIK-FORM, *ESI Group*, 99 Rue des Solets, Silic 112, 94513 Rungis-Cedex, France.
- Rudd C.D., Long A.C., Kendall K.N., Mangin C.G.E., "Liquid Moulding Technologies", 1997, Woodhead Publishing.
- ten Thije R.H.W., Loendersloot R., Akkerman R., "Material Characterisation for Finite Element Simulations of Draping with Non-Crimp Fabrics", *The 6th International ESAFORM Conference on Material Forming*, Salerno, Italy, 2003, pp. 859-862.
- TECABS: "Technologies for carbon fibre modular automotive Body Structures", Framework V project G6RD-CT2001-00636, <http://www.tecabs.org>, 1998-2002.
- Trochu F., Hammami A., Benoit Y., "Prediction of Fibre Orientation and Net Shape Definition of Complex Composite Parts", *Composites: Part A*, Vol. 27A, 1996, pp. 319-328.
- Van West P.B., Pipes R.B. and Keefe M.J., "A Simulation of the Draping of Bidirectional Fabrics Over Arbitrary Surfaces", *Journal of the Textile Institute*, Vol. 81, No. 4, 1990, pp. 448-460.
- Wiggers J., Long A., Harrison P., Rudd C., "The Effects of Stitch Architecture on the Shear Compliance of Non-Crimp Fabrics", *The 6th International ESAFORM Conference on Material Forming*, Salerno, Italy, 2003, pp. 851-854.