<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper published in *Composites. Part A, Applied science and manufacturing*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Larberg, Y., Åkermo, M. (2014)

In-plane deformation of multi-layered unidirectional thermoset prepreg - Modelling and experimental verification.

Composites. Part A, Applied science and manufacturing, 56: 203-212

<http://dx.doi.org/10.1016/j.compositesa.2013.10.005>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-106510>

In-plane deformation of multi-layered unidirectional thermoset prepreg – modelling and experimental verification

Ylva Larberg* and Malin Åkermo

Department of Aeronautical and Vehicle Engineering

Kungliga Tekniska högskolan

SE-100 44 Stockholm, Sweden

Abstract

Sheet forming of unidirectional prepregs is gaining increased interest as a cost efficient alternative manufacturing method. Its potential lies within the use of automatically and efficiently stacked flat prepregs, which in a second step can be formed. A successful forming requires understanding of the properties of the uncured material. Here, the in-plane deformation behaviour of two different unidirectional thermoset prepregs is investigated. Experimental measurements are performed, showing the importance of stacking sequence and its effect on the forming behaviour of stacked prepreg. Finite element models are developed, using material models calibrated from bias extension tests and interlaminar friction tests. The method developed can be used to predict the reaction force and fibre reorientation during in-plane forming of thermoset prepreg, for one of the considered material systems. Further, it enables prediction of the effect of stacking sequence, which is promising for future full-scale forming simulations.

Keywords: A. Carbon fibres, prepreg C. Finite element analysis (FEA), E. Forming

*Corresponding author. E-mail address: larberg@kth.se

1 Introduction

In manufacturing of advanced thermoset composites several process steps of different physical nature are involved, as e.g. layup and forming, consolidation and/or impregnation and curing. The understanding of each specific step is crucial, since they all affect the quality of the final component. To further understand the influence of forming on the part quality, attempts to model this process have been made. The aim of modelling forming is, for example, to predict the correct fibre angles as an input to calculate stiffness and strength, and its influences on shape distortions [1-3]. Also finding flaws as wrinkling formation and thickness variations, as e.g. corner thinning [4], are of great interest.

Research published on forming of composites is commonly based on weaves, often with the aim to predict the change of fibre angles [5-8] and to identify areas difficult to form. Single layers of unidirectional (UD) prepregs are generally considered to only deform through shear between the fibres, i.e. in the soft but weak matrix [9]. However, additional deformation mechanisms are present when forming stacks of UD prepreg, since the tacky semi-cured resin provides a coupling between the layers. This coupling both restricts slippage and enables fibre rotation within the stack, which to some extent can be compared to the physical link of the weave's interlacing [10, 11].

Forming of stacked thermoset UD prepreg laminas are commonly performed at elevated temperatures to lower the ply/ply (interply) friction, intraply shear and thereby enable bending and local stretching around corners etc. The forming load may be applied using compression moulding facilities; however, since this does not enable applying pressure perpendicular to the compression direction, different types of flexible diaphragms are often used instead. The diaphragm, commonly pressurised using vacuum, is placed to cover the material and mould. The uncured composite stack is formed by the pressure created as the rubber is stretched. Forming occurs in-plane, out-of plane and in the direction perpendicular to the mould, where the in-plane shear is of outermost importance to enable adaption to the three dimensional geometry, see e.g. [10]. The current study aims to investigate if the in-plane shear properties of stacked UD prepreg can be improved by proper selection of the stacking sequence.

The presented work further aims to develop a methodology, enabling modelling the in-plane deformation for different stackings using a finite element (FE) method. Since multi-layer forming relies on a coupling in-between the layers, which cannot be modelled by traditional mapping techniques, a continuum mechanical approach is herein used for the FE-modelling. The elements have separate in-plane and out-of-plane properties, which in combination with contact models makes it is possible to simulate forming of multi-layered composites with large deformations. The in-plane forming simulations are compared to experimental results and the developed methodology is thereby assessed.

2 Deformation mechanisms and material properties

Previous experimental results have shown that forming is influenced by the uncured material properties of the lamina; the stiffness and strength of fibres, the geometrical properties of the ply, such as thickness of the ply [8, 12], resin compound, the degree of impregnation and the level of consolidation [13, 14]. The deformation mechanisms generally considered occurring during forming are intraply shear, intraply tensile/compressive loading, interply (ply/tool or ply/ply) shear, ply compaction/consolidation (including resin percolation) and ply

bending [15]. Here, with focus on in-plane behaviour, ply bending is not included in the following description of the forming mechanisms.

The intraply shear properties can be divided into two types: through the thickness and in-plane shear; Figure 1 shows the difference. The through thickness intraply shear occurs during out-of-plane forming and is therefore not further considered here. During in-plane shear the fibres reorient to conform to the shape of the tool, which is often seen as the most important measure when it comes to forming. For weaves, a limit of in-plane shear deformation is often defined as the shear locking angle, although this does not seem to exist in the same way for cross-ply UD prepreg [11, 16, 17].

The interply (ply/ply) friction improves the forming behaviour of cross-ply UD prepreg by serving as a connection between the plies [10], but may also introduce wrinkles if not properly controlled [18]. Interply tool/ply friction influences the stress-build up, which, if remaining after curing, results in residual stresses influencing the shape distortions [2, 3, 19]. The importance of taking the interply friction into account is stated by for example Gorczyca-Cole et al [20], Vanclooster et al [21] and ten Thije et al [22], all studying thermoplastic composites. They all claim that the interply mechanism is necessary to include achieving a realistic simulation of a multi-layered stack during forming. Gorczyca-Cole et al and Vanclooster et al use the Stribeck theory [23], calibrated by experimental tests. The friction model is implemented as a subroutine in the commercial FE-software ABAQUS.

Consolidation is often the first step during a cure cycle where a combination of pressure and temperature forces the material to the cured ply thickness (CPT). In an earlier study, consolidation has been seen to change the interlaminar friction [14], either increasing or decreasing the resistance to slide. Hubert and Poursartip [13, 24] stresses the importance of knowing the flow and compaction during autoclave processing, since it affects the final thickness profile, residual stresses and distortion of the composite. Although its importance, it is not further investigated within this study.

3 Modelling

To predict forming of fabrics, weaves and UD prepregs there are several ways to proceed. The easiest, and the oldest, is the so called mapping technique, also known as kinematic modelling. The mapping technique treats the weave/layer as a pin-jointed net (PJN) of fibres, considered as inextensible with no thickness and width [25]. Material properties are not included and modelling is only affected by the geometry of the tool and the initial point/path of contact. It is a computationally very efficient method, but can for example not capture interply friction, out of plane wrinkling or take boundary conditions into account [26-28].

The alternative to mapping techniques is often referred to as the mechanical approach, which requires the constitutive behaviour of the materials as input. The mechanical approaches have the possibility to make good predictions by the use of an FE formulation and constitutive material models [9, 29], but at a cost of large CPU-time and the effort of retrieving accurate material data. By using the mechanical approach both realistic material models and boundary conditions can be implemented. The mechanical approach can be divided into three branches: discrete, continuous and semi-discrete, which all consider the macroscopic deformation behaviour of the fabric/sheet [30]. The discrete case treats the yarns as beams or trusses and the interactions are modelled using i.e. springs, see [31, 32]. Yarn directions are easily tracked, but it comes to a relatively high computational cost limiting the size of the simulated geometry [30]. The second method considers the fabric/sheet as an anisotropic and homogeneous continuum; here, shell and membrane elements can be used. This continuum model requires a method for tracking the fibre direction throughout the simulation. The combination of these two methods is called the semi-discrete and was presented by Hamila et al [33], further developed by Boisse et al [18]. The base is a three-noded element including the properties of a unit cell of weave or fabric. The properties taken into account are tensions, in-plane shear and bending stiffness. This model neglects the presence of matrix and its influence on forming, which in many cases has a crucial effect on the result [14, 21, 34-36].

4 Method

The influence of stacking sequence, on the in-plane deformation of stacked UD prepreg, is experimentally investigated using a modified bias extension test, see chapter 6. The method, see Figure 2, includes the use of a decoupled, continuous and large deformation FE approach. This requires selection of constitutive material models, which can describe the behaviour observed during experiments. The models are calibrated, thereafter used in FE simulations and verified towards the in-plane forming behaviour of different stacking sequences. The future aim is to include these in-plane material models as a part of the behaviour of a full-scale 3D forming.

5 Materials and characterisation of forming properties

This study focuses on two aerospace graded thermoset epoxy/carbon prepreg materials:

- HexPly® T700/M21, 268g/m² (referred to as T700/M21) from Hexel
- Cycom® HTS/977-2, 134g/m² (referred to as HTS/977-2) from Cytec

The systems are certified to be used in primary aircraft structures and aimed to be cured at 180°C. The fibres volume fraction is 57% for T700/M21 and 58% for HTS/977-2. The unconsolidated ply thickness of T700/M21 is 0.32mm and for HTS/977-2 0.14mm. The HTS/977-2 is toughened with liquid thermoplastic, while the T700/M21 material includes thermoplastic particles. The particles have been seen to affect the forming in terms

of friction [14] and resin flow during cure. Forming of these prepreg systems is usually performed at elevated temperatures, but is always kept below 90°C to prevent undesired curing. The characterisation of the forming properties of these two materials is further described below.

5.1 Intraply properties

The intra-ply properties for cross-ply UD T700/M21 and HTS/977-2 are measured in an earlier study [17] using the bias extension test method. Bias extension is an off-axis tensile test for measuring the un-cured shear properties, described in more detail in [11, 17]. The method is commonly used for weaves, but can also be used for cross-ply UD prepreg if the integrity of the stack is sufficient. The theoretical fibre rotation is calculated based on the theory of PJN and geometry of the sample [11]. Although this method aims to introduce pure shear in the material, it will also allow slip between layers when the resistance to rotate is larger than the interlaminar friction. In the current tests, the load is recorded by the tensile testing machine while the fibre rotation is evaluated by a digital image correlation (DIC) method. The outer specimen dimension is 250x50 mm² and the thickness depends depending on material and number of layers. Here, results from tests of T700/M21 at 85°C and HTS/977-2 at 70°C, both at a constant cross-head rate of 40mm/min, are used.

5.2 Friction properties

To measure the interply friction between prepreg plies a test rig was developed in a previous study, see [14]. The apparatus consists of one pneumatic cylinder and three plates holding the prepreg: one large, 150x200mm², fixed to the lower beam of the Instron 4505 testing machine and two smaller plates, 100x90mm², moving upwards as the test starts. This design results in a constant contact area, tested at a specific pressure and pulling rate. To obtain isothermal conditions at elevated temperatures the apparatus is mounted inside a heating chamber, specially designed to fit the Instron 4505. Results from tests performed at 85°C for T700/M21 and 70°C for HTS/977-2 are used here and the extracted friction coefficients can be seen in Figure 3. Both materials are tested at three different pulling rates of 0.05mm/min, 0.1mm/min and 1mm/min. The tests were performed at 80kPa for the T700/M21 material and 53kPa for the HTS/977-2 material, where the selection of different pressures are due to historical reasons.

6 In-plane testing of stacked UD prepreg

In an attempt to investigate the effect of stacking sequence on the in-plane forming, layers transverse to the pulling direction, here called 90°-layers, are included in the bias-extension test. Two stacking sequences, [45/-45/90]_s and [45/90/-45]_s, are tested experimentally, where fibre rotation of the top ply and load response are registered as described further below. Figure 4 shows that by stacking the -45° and 45° plies adjacent to each

other, the resulting deformation mechanisms may be in-plane shear resulting in fibre rotation. The interfaces where 45° and 90° layer are adjacent may experience a combination of interlaminar slippage and fibre rotation. Since the second stacking sequence considered is lacking $\pm 45^\circ$ -interfaces, the degree of potential shear is reduced, see Figure 5. This minor change in stacking sequence may therefore have a significant impact on the in-plane forming behaviour.

An Instron 4505 machine equipped with a 5kN load cell is used for all tests. The specimen is held in place with pneumatic grips with a clamping force of 1kN. To control the temperature an environmental chamber surrounded the test set-up. To eliminate the noise from the load cell, the load is filtered by a butter filter in MatLab. The error bars represent the spread of three tests, calculated by standard deviation.

The rotation of the fibres on the surface of the material stack is traced using a DIC system. The system is capable to measurement three-dimensional deformation and strain, but due to difficulties with the calibration through the glass window of the environmental chamber, only 2D deformation analyses are considered in this study. The resolution of the camera used is 1.3MP (approximately 8 pixel/mm) and the facet size (a group of measuring points) is never less than 2.5mm. The results are averaged from three samples and compared to the theoretical fibre rotation predicted by PJN theory.

Each specimen consisted of six equally sized prepreg layers. To achieve a uniform contact between the layers, the pieces are consolidated under vacuum at room temperature for at least 30 min at -0.1MPa pressure. Each sample has an ungripped sample size of 250x50mm and the nominal thickness is 1.9mm for T700/M21 and 0.8mm for HTS/977-2. The materials are tested at the same temperatures as in friction and shear, 85°C for T700/M21 and 70°C for HTS/977-2, and at a cross-head rate of 40mm/min.

7 FE modelling

In this work, the AniForm Virtual Forming Tool [37] is used for predicting the in-plane deformation of stacked UD thermoset preregs. AniForm is based on a continuum mechanical approach solved by an FE method, offering a simulation tool that can handle large-strains and time-dependent material models. The plies are modelled as decoupled shells, which means that the bending properties are described in continuum shell elements and the in-plane behaviour is included in continuum membrane elements. This coupled element is called a 2.5D element, shown for the xz-plane in Figure 6.

Parameters required for the constitutive material models chosen are retrieved from experimental data. Decisions on which constitutive material models to use are based on the observed behaviour during experimental tests and to a certain extent the available data. Here, the results from interlaminar friction tests and bias extension

tests are used for calibration of the constitutive material models. The parameters required for the material models are attained by fitting analytical models towards measured reaction loads, as further described below. These calibrated values are thereafter used as input to the FE simulation of the bias extension test. Results from simulations are compared to experimentally measured loads and fibre rotations from bias extension tests.

7.1 In-plane shear models

A reinforced Kelvin-Voigt model is used to model the in-plane shear, consisting of an isotropic elastic (spring) material model together with a Newtonian fluid (damper). In addition to this, the fibres are modelled using a linear elastic fibre model, defined with respect to the elements local coordinate system. Fibres can be added in an arbitrary initial fibre direction. Assuming that the bias-extension test, $[45/-45]_s$, corresponds to pure shear, the membrane shear properties can be calibrated by using the measured data. By using analytical material model expressions within a MatLab-script, provided by [37], a least square fit towards the experimental values given by a load-displacement curve is performed. Since all simulations within this study are in the plane, the bending part is not active. The material models for the membrane part, corresponding to the continuum including both fibre and matrix, are given in Table 1.

Due to large differences between the material properties, the value of the fibre stiffness, E , is reduced compared to the real value. This will give a more stable simulation and does not affect the results.

7.2 Contact modelling

The contact between the prepreg layers are, as a result of experimental characterisation [14], described by a combination of Coulomb friction, viscous friction and adhesion. The Coulomb friction represents the friction between two solid surfaces and is given by a friction coefficient independent of pressure and speed. The Coulomb friction model in the FE-code includes a penalty stiffness model which is required as contact condition for the numerical simulation in order to prevent penetration of between surfaces in contact. The viscous friction is based on Reynolds' model of a hydrodynamic film [37]; defined by a film with a certain thickness, h , and viscosity, η , according to:

$$\tau_{xy} = \eta \dot{\gamma} = \eta \frac{v_{xy}}{h}, \quad (1)$$

where τ_{xy} is the traction force and $\dot{\gamma}$ is the shear rate. By studying the equation it can be seen that the viscous friction is dependent of both speed and temperature (viscosity). In addition, a material model for the tacky properties of the surface is included and called adhesion. This adhesion is activated if the layers are or come in contact during the time dependent forming simulation. When active, the adhesion ascertains contact between

layers independent of pressure, and is released if the tension exceeds a given value. The adhesive model will cause a small penetration of the surfaces in contact, leading to an active model for the viscous friction. In this case a low value for adhesion is sufficient to cause the penetration needed.

The traction force, force/area, from the interply test is extracted and used to calibrate frictional properties between layers and implemented in the model. By utilising a MatLab-script provided by [37] the model parameters for the chosen models are calibrated towards the analytical models chosen to represent the contact modelling. The calibration aims to fit the values of the models to the traction force, given by interlaminar friction tests, presented in Figure 3. For the PenaltyCoulomb model the friction coefficient is calibrated, while values for penalty stiffness and slip control are chosen to be low. In this particular case these factors have a negligible influence on the result. The values used for the contact material models are presented in Table 2.

7.3 Modelling of in-plane deformation of stacked UD prepreg

In order to validate the developed material models, the bias-extension test $[45/-45]_s$ is also modelled in AniForm. Each ply has an initial size of $250 \times 50 \text{ mm}^2$, see Figure 7. The lower clamping is modelled by locking the edge nodes in all translational degrees of freedom. The upper clamping, moving up during test, is constructed in the same way but here only the horizontal degree of freedom is locked. Each layer consists of 500 triangular 2.5D elements. The in-plane forming tests with the stacking sequences including 90° -layers ($[45/-45/90]_s$ and $[45/90/-45]_s$) are modelled by using the same calibrated material models as for the bias extension test. Also, mesh size and boundary conditions are equivalent.

8 Results and discussion

This section will include results from both experimental tests and numerical simulations. The fibre rotations are measured on the surface ply in the middle of the sample, both for experiments and in simulations. Since the shear properties are calibrated towards experimental results from bias extension tests, $[\pm 45]_s$, these values are presented for comparison and as reference. Therefore, the load to deformation is normalised with respect to sample thickness to enable comparison between different stacking sequences and materials.

8.1 Experimental results

Visual observations of the samples during in-plane deformation tests confirm that the stack deforms together rather than as single plies. Substantial shear deformation is obtained due to the tacky coupling between the layers. Without this coupling, each ply would deform separately, shown as a widening of the sample for a 45° -ply [38]. As a result of the shear in the $\pm 45^\circ$ -layers, contraction of the plies width are taken place as it deforms, showing the edges of the 90° -plies which are unable to contract.

Figure 8 shows the load responses and the fibre rotations for three different stackings of T700/M21. As can be seen, the $[45/-45]_s$ stacking requires the lowest load to deformation and rotates seemingly according to the PJN theory. Figure 8a further shows that by adding 90° -layers, the load to deformation is significantly increased compared to the $[45/-45]_s$. Differences between the stackings with 90° -layers can be seen in the load responses, where $[45/90/-45]_s$ shows the highest values. For $[45/90/-45]_s$ the fibre rotation seems to be restricted by the 90° -layer, while the $[45/-45/90]_s$ stacking still compares well to the PJN prediction for the first 5mm. Worth noting is the decrease in load level after 5mm displacement for both stacks including 90° -layers, but more pronounced for $[45/90/-45]_s$. The decrease in load is caused by splitting of the surface layer, which is also observed at around 5mm for the $[45/-45]_s$ [17]. Since splitting starts at different places and the fibre angle is evaluated at the same location, the DIC sometimes captures what is movement due to splitting as an addition to the rotation. This increases the scatter of the measurements; as a result a large spread is seen in Figure 8b.

T700/M21 seems to behave according to PJN for stacking sequences including the coupling between $\pm 45^\circ$ -plies; however, a related study [39] shows that for a stacking sequence of $[30/-30]_s$, or lower angles, the material undergoes substantial slippage where the PJN approximation is consequently not valid anymore.

For HTS/977-2 the behaviour is different compared to the T700/M21 material, see Figure 9. First, it can be noticed that the load to deformation for $[45/-45]_s$ is only a third of the measured load for the T700/M21 material, (compare Figure 8a and Figure 9a). Also here, the $[45/90/-45]_s$ show a higher resistance to deformation compared to $[45/-45/90]_s$. In addition, the measured fibre rotation is significantly lower for HTS/977-2 than predicted by PJN. This is due to slippage between the layers, during the bias extension test. Figure 9b shows that, in the same way as for the T700/M21 material, the fibre rotation for the $[45/-45/90]_s$ stack is the same as for $[45/-45]_s$. The fibre rotation for the $[45/90/-45]_s$ stack is significantly lower than for the other two stackings; just as for the T700/M21 material. For HTS/977-2 no obvious splitting is seen visually, as a consequence the deviations in load response and fibre rotation are almost constant.

To summarise the experimental findings; the coupling between the $\pm 45^\circ$ -layers seems to be very important for the fibre rotation and by placing the 90° -layer between them the deformation behaviour is different.

8.2 Numerical results and experimental verification

For visual clarity, experimental data is hereafter only presented as average values without standard deviations. Reaction forces from simulations of bias extension tests are compared to experimentally measured loads in Figure 10. As can be seen, the FE-model predicts the load to displacement with good correlation for both

materials. However, there is a big difference in the ability of the developed FE-model to predict the fibre rotation.

Figure 11a shows that the model for T700/M21 predicts the fibre rotation very well. For HTS/977-2 on the other hand, the fibre rotation is overestimated compared to experimental data, see Figure 11b. This difference, approximately 25%, is due to more slippage between layers in the experiments compared to the simulation. This slippage will occur if the frictional resistance is lower than the resistance to shear. The method of calibrating shear properties, described earlier, assumes no slippage only pure shear, hence the difference.

From the following it can be concluded that the herein used shear model is underestimating the resistance to shear for materials experiencing slip: The calibration is based on the measured load to deformation, which due to slippage is lower than it would be for pure shear. At the same time, in the calibration this low, measured value is treated as corresponding to pure shear, i.e. related to a higher degree of fibre rotation than it actually is.

Attempts have been made to improve the calibrated model by changing the input data according to the following: The experimentally measured load to deformation is still used in the calibration, but the related deformation is calculated in reverse based on the measured fibre rotation, i.e. neglecting all influences from slippage on measured load and eliminating the influences on slippage from the deformation. This should result in more accurate shear models; however, it did not significantly change the modelling outcome.

To further investigate this for materials experiencing slip during bias extension, a different method to measure shear is required. The picture frame test is one example, although introducing other issues such as fibre misalignment and edge effects could cause large variations [5]. New test methods are currently under way, as e.g. [35]; however, not available at the time of testing.

8.3 Predicted deformation of stacked UD prepreg

Figure 12 shows a comparison for T700/M21 between the simulated deformation and experimentally measured results, for the two layups including 90°-layers. As shown, the predicted behavior is in good agreement with the test results. The simulations enable predicting the difference in load to deformation for the two different stackings. Further, the prediction of fibre rotations agree well with the averaged measured fibre rotation, at least until the initiation of splitting at around 5mm, see Figure 12b. For the [45/90/-45]_s layup, the predicted fibre rotation correlates with measurements until a higher level of deformation.

Figure 13 shows the simulated load to deformation for the HTS/977-2. As can be seen, the predicted reaction loads are much higher than the experimental values. However, in Figure 14, the fibre rotation still shows

a good agreement for the $[45/90/-45]_s$ layup, at least for the first part of the deformation. It is also seen that $[45/-45/90]_s$ show an overestimation of fibre rotation, as earlier shown in the $[45/-45]_s$ -case.

As discussed previously, the calibration of the HTS/977-2 results in an underestimation of the intraply shear of the material. The predicted results are therefore surprising and can not only be related to errors in the shear calibration routine. The other option would be errors in the model describing the interply friction. The calibration of the interply friction is based on experiments, where the fibre directions of the plies are parallel to each other and aligned in the pulling direction, so called $0^\circ/0^\circ$. This is not the same as in the current layup. Recently, an internal study showed that the angle between the interfaces affects the friction resistance; where the $0^\circ/0^\circ$ interface shows the highest friction. Further, the interply friction model is calibrated based on experimental data obtained when the samples are under a low, but constant normal load. In the current test no normal load is present, making the influence of the viscous friction dominant.

In order to investigate the influence of the interply friction in the model, the viscous friction is reduced between the layers. This is done by including a multiplier, a viscous friction factor, reducing the interply friction. The value, 0.3, is selected to improve the coherence. By using this factor in the simulation of the $[45/-45]_s$ test only a marginal increase in the load was seen, while for the stacks with 90° -layers the effect was significant. As can be seen in Figure 15, for the $[45/90/-45]_s$ and $[45/-45/90]_s$, the load to deformation was significantly reduced showing the correct difference between the stackings and in much better agreement with the experimental measurements. The fibre rotation shows a very small increase, compare Figure 16 and Figure 14.

Another interpretation of the differences shown between the two material systems behaviour, may be due to the constitution of each ply. Figure 17 shows scanning electron microscope (SEM) pictures of the two different virgin materials. As can be seen in Figure 17a, the HTS/977-2 consists of one layer of fibre tows that may be expected to split apart when loaded in the transverse fibre direction. The T700/M21 material, on the other hand, is thicker and contains several layers of fibre tows that may cover potential gaps developed from transverse testing, see Figure 17 b. This issue needs to be further investigated; however, it seems like the required improved method for calibration of the intraply shear properties does not solve the entire issue for this material system.

9 Conclusions

This study aimed to develop and verify a modelling methodology for predicting the in-plane deformation behaviour of stacked unidirectional prepreg materials. Two different carbon/epoxy systems certified for use in the aerospace industry were used: T700/M21 and HTS/977-2. The influence of stacking sequence on the in-plane

deformation was studied experimentally and through FE-modelling. Two stacked UD prepreg layups were studied, $[45/90/-45]_s$ and $[45/-45/90]_s$.

In the evaluation of the experimental and numerical results, the overall load-deformation response and the fibre rotation of the outer 45° -layer were investigated. The in-plane load-deformation response differed significantly between the two material systems for the considered layups. In general, the T700/M21 showed a much higher load response in comparison to HTS/977-2.

In addition, a difference in fibre rotation between the materials was observed, where the T700/M21 deformed close to pure shear deformation, meaning no interply slippage, while the HTS/977-2 did not. The HTS/977-2 material underwent substantial slip when tested in bias extension, resulting in a lower fibre rotation compared to what was expected based on the pure shear estimation.

Different deformation mechanisms were also observed for the two different layup configurations with 90° layers. For the lay-up with 90° fibre layers positioned in the centre of the stacking, i.e. $[45/-45/90]_s$, the fibre rotation was close to the results from $[45/-45]_s$, for both material systems. For the layup with 90° fibre layers in-between the two bias layers ($[45/90/-45]_s$) a reduced fibre rotation (up to 50%) was observed in combination with an increased load to deformation.

The herein developed finite element material models predict both the load to deformation and the fibre rotation well for the pure bias samples, $[45/-45]_s$, and the stacking sequences including 90° -layers for the T700/M21 material.

For HTS/977-2, on the other hand, the calibration of the material shear properties did not succeed, partly due to the fibre slippage during the experimental tests. In addition, upon using the model for predicting the shear to deformation for the samples with 90° fibre layers, the load to deformation was significantly over-estimated. The large difference between predicted and measured load could only be explained by additional problems with the formulation of the interply contact expressions. However, this requires further investigation.

This study concludes that the in-plane deformation behaviour differ significantly in-between different multi-layer stacking sequences. It is however possible to capture this in modelling using continuum membrane elements with material models calibrated from experimentally measured values for the T700/M21 material system. The next step is to develop a method to calibrate the out-of-plane properties and adding the shell part of the decoupled element, to enable full-scale simulations of sheet forming.

Acknowledgements

The study is a part of the research project PRICE (Focus on Producibility) lead by Saab Aerostructures in Linköping. Funding for the project is provided by NFFP (National Aviation Engineering Research Programme) and is gratefully acknowledged. The cooperation with Per Hallander, Mikael Petersson and Tonny Nyman is appreciated and inspirational. Funding provided by XPRES (KTH Initiative for Excellence in Production Research) is also gratefully acknowledged.

References

1. Lamers EAD. Shape distortion in fabric reinforced composite due to processing induced fibre reorientation. PhD Thesis, 2004. University of Twente.
2. Potter KD, Campell M, Langer C, Wisnom MR. The generation of geometrical deformations due to tool/part interaction in the manufacture of composite components. *Compos Part A* 2005;36:310-308.
3. Ersoy N, Potter K, Wisnom MR, Clegg MJ. An experimental method to study the frictional processes during composites manufacturing. *Compos Part A* 2005;36:1536-1544.
4. Fernlund G, Griffith J, Courdji R, Poursartip A. Experimental and numerical study of the effect of caul-sheets on corner thinning of composites. *Compos Part A* 2002;33:411-426.
5. Harrison P, Clifford MJ, Long AC. Shear characterization of viscous woven textile composites: a comparison between picture frame and bias extension experiments. *Compos Sci Technol* 2004;64:1453-1465.
6. Mohammed U, Lekakou C, Dong L, Bader MG. Shear deformation and micromechanics of woven fabrics. *Compos Part A* 2000;31:299-308.
7. Wang J, Page JR, Paton R. Experimental investigation of the draping properties of reinforced fabrics. *Compos Sci Technol* 1998;58:229-237.
8. Wang J, Paton R, Page JR. The draping of woven fabrics and prepregs for production of polymer composite components. *Compos Part A* 1999;30:757-765.
9. Lim T-C, Ramakrishna S. Modelling of sheet forming: a review. *Compos Part A* 2002;33:515-537.
10. Potter K. Beyond the pin-jointed net: maximizing the deformability of aligned continuous fibre reinforcements. *Compos Part A* 2002;33:677-686.

11. Potter, K. Bias extension measurements on cross-ply unidirectional prepreg. *Compos Part A* 2002;33:63-73.
12. Lukaszewicz DH-JA, Potter KD. The internal structure and conformation of prepreg with respect to reliable automated processing. *Compos Part A* 2011;42(3):283-292.
13. Hubert P, Poursartip A. A method for direct measurement of the fibre bed compaction curve of composite prepreg. *Compos Part A* 2001;32:179-187.
14. Larberg YR, Åkermo M. On the interply friction of different generations of carbon/epoxy prepreg systems. *Compos Part A* 2011;42:1067-1074.
15. Long AC, Clifford MJ. Composite forming mechanisms and materials characterization. In: Long A, Editor. *Composites forming technologies*. Woodhead Publishing, Cambridge, 2007, p 1-19.
16. ten Thije RHW, Akkerman R, Huétink J. Large deformation simulation of anisotropic material using an updated Lagrangian finite element method. *Comput Meth in Appl. Mech. Engrg* 2007;196:3141-3150.
17. Larberg YR, Åkermo M, Norrby M. On the in-plane deformability of cross-ply unidirectional prepreg. *J Compos Mtrls* 2012;46:929-939.
18. Boisse P, Hamila N, Vidal-Sallé E, Dumont F. Simulation of wrinkling during textile composite reinforcement forming. Influence of tensile, in-plane shear and bending stiffness. *Compos Sci Technol* 2011;71:683-692.
19. Twigg G, Poursartip A, Fernlund, G. Tool-part interaction in composites processing. Part I: experimental investigation and analytical model. *Compos Part A* 2004;35:121-133.
20. Gorczyca-Cole JL, Sherwood JA, Chen J. A friction for thermostamping commingled glass-polypropylene woven fabrics. *Compos Part A* 2007;38:393-406.
21. Vanclooster K, Lomov SV, Verpoest I. Simulation of multi-layered composites forming. In: *Proceedings of ESAFORM-13 Conference, Brescia, Italy, April, 2010*.
22. ten Thije R, Akkerman R. A multi-layer membrane finite element for the forming simulation of laminated composites. *Compos Part A* 2009;40:739-753.
23. Hutchings IM. *Tribology: Friction and wear of engineering materials*. Anna Arbor CRC Press, 1992.

24. Hubert P, Poursartip A. Aspects of the compaction of composites angle laminates: An experimental investigation. *J Compos Mtls* 2001;35:2-26.
25. Mack C, Taylor HM. The fitting of cloth to surfaces. *J Text Inst* 1956;47:477-488.
26. Vanclooster K, Lomov SV, Verpoest I. Experimental validation of forming simulations of fabric reinforced polymers using an unsymmetrical mould configuration. *Compos Part A* 2009;40:530-539.
27. Hancock SG, Potter KD. The use of kinematic drape modeling to inform the hand layup of complex composite components using woven reinforcements. *Compos Part A* 2006;37(6):413-422.
28. Vanclooster K, Lomov SV, Verpoest I. Experimental validation of forming simulations of fabric reinforced polymers using an unsymmetrical mould configuration. *Compos Part A* 2009;40:530-539.
29. Akkerman R, Lamers EAD. Constitutive modelling for composite forming. In: Long A, editor. *Composites forming technologies*. Woodhead Publishing, Cambridge, 2007, p 22-44.
30. Vanclooster K. Forming of multilayered fabric reinforced thermoplastic composites. PhD Thesis, KU Leuven 2009.
31. Sharma SB, Sutcliffe MPF. A simplified finite element model for draping of woven material. *Compos Part A* 2004; 35(6) 637-43.
32. Skordos AA, Monroy Aceves C, Sutcliffe MPF. A simplified rate dependent model of forming and wrinkling of pre-impregnated woven composites. *Compos Part A* 2007; 38 1318-1330.
33. Hamila N, Boisse P. Simulations of textile composite reinforcement draping using a new semi-discrete three node finite element. *Compos Part B* 2008;39: 999-1010.
34. Haanappel SP, ten Thije R, Akkerman R. Forming predictions of UD reinforced thermoplastic laminates. In: *Proceedings of ECCM 14, Budapest, Hungary, June, 2010*.
35. Haanappel SP, ten Thije R, Akkerman R. Constitutive modelling of UD reinforced thermoplastic laminates. In: *Proceedings of FRCM 10, Ascona, Switzerland, July, 2010*.
36. ten Thije RHW, Akkerman R. Finite element simulations of laminated composites forming processes. In: *Proceedings of ESAFORM 13, Brescia, Italy, April, 2010*.
36. AniForm Virtual Simulation Tool, software and help-manual, aniform.com.

38. Potter K. In-plane and out-of-plane deformation properties of unidirectional preimpregnated reinforcement. Compos Part A 2002;33:1469-1477.

39. Åkermo M, Larberg Y, Hallander P. Forming of advanced components out of pre-stacked cross-ply UD prepreg. In: Proceedings of ICCM-18, Jeju Island, Korea, August, 2011

Table 1. Material model parameters for the membrane part.

Membrane part				
Material			T700/M21	HTS/977-2
<i>Fibre</i>				
	<i>Linear elastic</i>			
	E	[MPa]	1000	1000
	Poisson	[-]	0.4	0.4
<i>Matrix/Fibre</i>				
	<i>Viscons</i>			
	viscosity	[MPa·s]	4.92	1.64
	<i>Linear elastic</i>			
	E	[MPa]	0.154	0.023
	Poisson	[-]	0.4	0.4

Table 2. Contact parameters used for ply-ply contact.

Contact logic ply-ply				
Material			T700/M21	HTS/977-2
<i>PenaltyCoulomb</i>				
	friction coefficient	[-]	0.15	0.013
	friction stiffness	[MPa]	0.05	0.05
	penalty stiffness	[MPa]	0.0075	0.0075
<i>Viscons friction</i>				
	film thickness	[mm]	0.0011	0.013
	viscosity	[MPa·s]	0.0011	0.0014
<i>Adhesion</i>				
	adhesion tension	[MPa]	1x10 ⁻⁸	1x10 ⁻⁸

Figure 1. Through thickness intraply (above) and in-plane intraply (below).

Figure 2. Methodology; from experiments to verification.

Figure 3. Interply friction a) T700/M21 and b) HTS/977-2, results used in calibration of friction models. Note different scales.

Figure 4. Stacking sequence [45/-45/90]_s (above) and expected, effective deformation behavior (below).

Figure 5. Stacking sequence $[45/90/-45]_s$ (above) and expected, effective deformation behavior (below).

Figure 6. 2.5D continuum element formulation in AniForm, figure from [37].

Figure 7. Bias extension test simulated in AniForm.

Figure 8. Experimental results from in-plane forming tests for T700/M21 at 85°C and 40mm/min.

Figure 9. Experimental results from in-plane forming tests for HTS/977-2 at 70°C and 40mm/min.

Figure 10. Loads from bias extension test compared to simulated load response for T700/M21 and HTS/977-2.

Figure 11. Rotation of fibres experimentally measured with DIC compared to AniForm model simulation, a) T700/M21 and b) HTS/977-2.

Figure 12. Fibre rotation (a) and load response (b) for T700/M21, stacking sequences [45/-45/90]_s and [45/90/-45]_s.

Figure 13. Experimental and simulated load response for HTS/977-2, stacking sequences $[45/-45/90]_s$ and $[45/90/-45]_s$.

Figure 14. Experimental and simulated fibre rotation for HTS/977-2, stacking sequences $[45/-45/90]_s$ and $[45/90/-45]_s$.

Figure 15. Load response for $[45/-45/90]_s$ and $[45/90/-45]_s$ for HTS/977-2, viscous friction factor of 0.3.

Figure 16. Fibre rotation and load response for $[45/-45/90]_s$ and $[45/90/-45]_s$ for HTS/977-2, viscous friction factor of 0.3.

Figure 17. SEM micrograph of virgin, uncured a) HTS/977-2 b) T700/M21, cuts are made transverse to fibre direction. (SEM situated at Dept of Fibre and Technology, KTH.)