FORMING OF ADVANCED COMPONENTS OUT OF PRE-STACKED CROSSPLIED UD PREPREG

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1 Introduction

With the increasing use of composite materials in civil aeronautical applications follow a demand for higher efficiency and reduced process cycle times. Considering manufacturing of structural components out of prepreg material, the focus is on the layup and forming process in order to avoid manual handling and tedious de-bulking steps. The presented work focuses on forming and possibilities offered by the sheet forming technique, where flat, pre-stacked prepreg material is allowed to be formed prior to (or as a first step in) the curing process. A typical set-up for sheet forming is shown in Fig.1.

Sheet forming is often performed using vacuum, where the pressure sequence, the mould geometry and properties of the stacked prepreg need to be accurately balanced to obtain a flaw free component. Common defects includes: material breakage due to too low forming temperatures, material thinning in corners, development of wrinkles, fibre miss-alignment and development of "mouse ears", as the pre-stacked material makes a larger radius than described by the mould. Development of mouse ears can be reduced ensuring that the lamina does not give too high resistance upon forming. Since the pre-stacked lamina is a viscous material, deformation resistance is governed by the interply (prepreg-prepreg) friction, intraply (within lamina) shear and matrix viscosity. However, comparing the results of earlier studies on in-plane shear deformation in the bias direction of cross-plied UD prepreg [1] and interply friction [2], it seems like shear deformation in the bias direction requires less energy than interplay slippage and therefor plays an important role in the deformation of the material and reduction of forming resistance. Experimental results have further shown that wrinkles that develop during forming can be eliminated by changing the stacking sequence of the pre-stacked lamina [3]. This spells out a need for a more detailed numerical model of the deformation of the pre-stacked lamina.

2 Background

Sheet forming of pre-stacked materials generally involves (mainly) shear in the bias direction, interply shear and intraply shear. The in-plane shear behaviour of a woven material in the bias direction is governed by the physical crosslinks limited by the crimp and therefore fairly well described by a geometrical model referred to as Pin Jointed Net theory (PJN) [4]; further commented on in the modelling section. For a woven material, shear in the bias direction is followed by fiber bed compaction and fiber rotation, locally changing the fiber angle of the deforming plies.

Previous studies on the in-plane bias shear of cross-plied unidirectional (UD) aerospace graded materials [1,5] has confirmed that although missing the physical links in-between the layers, also some UD materials deform according to the PJN when stacked in $[45/-45]_s$. Other materials deform like a continuous material, but undergo substantial slip compared to a woven material. For the third type of material investigated, the layers do not seem to hold together during deformation at slightly increased forming temperatures. The latter is visible as un-even deformation over the shear area and an s-shaped form of each deformed ply. Even though all materials initially deforms like a continuum, band formation occurs at higher degrees of deformation, whereafter the continuing deformation includes band-like interply slippage.

When a woven material is stacked together, the bias shear in each layer is still locked to follow the PJN theory due to the crimp. In a cross-plied UD material, on the other hand, it is not obvious at which interface she major sliding occurs; in-between the

$[45/-45]_s$ layers or at the interface(s) towards the adjacent layer(s). To date, no study has been found addressing this issue. A good summary of forming of composite materials can be found in e.g. [6].

3 Aim of Work

The presented work aims to investigate the load to deformation and fibre rotation for other fibre lay-up than $[45/-45]_s$ in order to determine if the deformation behaviour changes for these layups towards increased slippage. Further, the experimental study aims to investigate the influence on the bias shear behaviour of adding one further fibre angle; i.e. two different combinations of $[45/-45/90]_s$ stacking sequences are investigated.
The findings are calibrated towards commercial Finite Element based software, initially developed for thermoplastic prepreg materials, with the aim to investigate if the software enables predicting the experimentally observed in-plane deformation behaviour of cross-plied UD prepreg material.

4. Experimental study on the formability of pre-stacked prepreg

To determine the deformation resistance and deformation mechanisms for crossplied UD prepreg, bias extension tests are performed. The metod is preferred since it, in contradiction to the picture fram method, allows for inter-ply slippage. Further information on this method in comparison to others methods available can be found in e.g. [7,8]

4.1 Materials

The prepreg material systems used are aerospace graded UD carbon/epoxy systems:

- HexPly® T700/M21 (referred to as M21), Hexel
- Cycom® HTA/977-2 (referred to as 977-2), Cytec

977-2 has a fibre volume fraction of 0.57 and an uncured ply thickness of 0.14 mm, while the fibre volume fraction of M21 is 0.57 and thickness 0.30 mm. The materials belong to different generations of prepreg, where M21 include unsolved tougheners of thermoplastic particles, while with 977-2 the thermoplastic toughener is liquid.
Five different layups were investigated herein: $[22.5/-22.5]_s$, $[30/-30]_s$, $[45/-45]_s$, $[45/90/-45]_s$ and $[45/-45/90]_s$. The layers were put together prior to testing using vacuum pressure (1 bar) ensuring a constant and repeatable joining force.

4.2 Test procedure

Test were performed in an Instron testing device (load cell 5 kN) equipped with a heating chamber to enable testing at elevated temperatures. The samples were 250 mm long (ungripped sample length) and 50 mm wide. Machine speed was adjusted to obtain a shear strain of 20%/min, which equals 40 mm/min for the $[45/-45]_s$ samples. The 977-2 material was tested at 70°C, (matrix viscosity 120 cP), while the M21-material was tested at 60°C and 85°C (matrix viscosity 1500 cP and 90 cP, respectively) to enable comparison to previous tests [1,2].
Except for load to deformation, measured by the in-built load cell and data accquissation system, the deformation was followed using a contact free measuring technique named Digital Speckle Photography (DSP). Further information on sample preparation and testing procedure can be found in Ref 1.

4.3 Results from bias extension tests

Load to deformation
The load-deflection curves for the different stackings investigated can be found in Fig. 2; where upper figures shows the results from the M21 sample tested at 60°C and 85°C, respectively, and the figure at the bottom shows the results from tests on 977-2. As can be seen, load curves from samples consisting of 6 layers are divided by 1.5 in order to enable comparison to the 4 layer samples.
As shown in the figures, the load to deformation is generally much higher for M21 than for 977-2 (please note that the 977-2 samples has half the thickness of the M21 samples). This is in agreement with previous observations [1]. The difference is naturally less comparing to M21 tested at 85°C, where the viscosities of the two matrix materials are fairly similar. One reason for the higher deformation resistance of M21 is believed to be that the toughening particles are situated mainly in-between the fibre layers, resulting in a matrix rich interface and a locally higher fibre volume fraction in the fibre bundles, thus requirering a heigher load to deformation

[1]. A previous study has shown that M21 measures higher interply friction than 977-2 [2], however, as will bee seen later, since no interply slippage can be observed for the M21 $[45/-45]_s$ stacking, this should not make a significant difference.
Fig. 2 futher shows that the load to deformation is significantly dependent on the fibre layup: for the M21 material, the load to deformation is approximately 5 times higher for the $[22.5/-22.5]_s$ layup than for the $[45/-45]_s$ layup. For 977-2, the difference is even larger: 10 times higher. For both materials, the $[30/-30]_s$ layup gives a resistance to deformation inbetween the previous. For the M21 $[22.5/-22.5]_s$ samples tested at 85°C, the load to deformation reduces at higher deformations, which could possibly be explained by that the fibre tows swells away from the interply interfaces during deformation, reducing the degree of contact. For 977-2 and M21 at 60°C, on the hand, the load continues increasing almost linearly.
Adding further layers of material in the transverse direction significantly contributes to the resistance of deformation. As can be see in Fig. 2, the $[45/90/-45]_s$ layup generally shows a higher resistance to deformation than the $[45/-45/90]_s$ layup and the load is raising much faster than for the latter layup. For 977-2 the load to deformation increases with a factor of 5 when adding extra fibre lyers in the transverse direction, for M21 the difference is roughly a factor of 2-3 depending on temperature. Further, it can be observed that for 977-2, the load to deformation for both 6 layer combinations initially behaves similar to the $[45/-45]_s$ layup. For test on M21 performed at 85°C, the load to deformation for the $[45/90/-45]_s$ layup initially increases with the same slope for the as the $[22.5/-22.5]_s$ layup, while the $[45/-45/90]_s$ layup initially behaves as the $[45/-45]_s$ layup.
Early results from large scale experiments in the work shop indicate that the initial difference in deformation resistance may make a hugh difference in the forming outcome during sheet forming of complex components.

Fibre rotation
Fibre rotation during bias extenstion testing for the different layups are shown in Fig. 3. The results for the different 6-layer layup with M21 are shown together with simulation results in Fig. 5. As can be seen, for both M21 and 977-2, fibre rotation is significantly lower than theoretically predicted (PJN) for the $[22.5/-22.5]_s$ layup. For M21, the fibre rotation at $[30/-30]_s$ is approximately 75% of the rotation given by the PJN for that stacking, For 977-2, the fibre rotation for the $[30/-30]_s$ layup is around 70% of theoretical value, which is similar to the $[45/-45]_s$ layup for that material.
The results confirm that for M21, the $[45/-45]_s$ layup deforms in accordance to the PJN theory. However, for all tests performed at smaller layup angles, substantial slip occurs. In spite of the very large difference in matrix viscosity at 60°C and 85°C (1500 and 90 cP, respectively), the measured fibre rotation seem to coinside for all M21 layups. The prepreg-prepreg interply friction [2] has previously been reported to be fairly constant for M21 at the considered temperatures. Since the rotation is similar, it is expected that the big difference in forming resistance, is mainly due to difference in intraply shear behaviour, such as resistance to fibre bed compaction and intraply slippage
As shown in Fig. 5 and in accordance with the observations from the load to deformation curves, the M21 $[45/-45/90]_s$ layup (tested at 85°C) initially deforms according to the PJN theory, however at higher deformation levels the fibre rotation is reduced to the same slope as the $[45/90/-45]_s$ layup. For the same stacking sequence tested at 60°C, the rotation is similar, but the deviation from PJN prediction slightly larger. For 977-2, on the other hand (Fig. 3), both 6 layer combinations show a fibre rotations initially similar to that measured for $[45/-45]_s$ layup. However, measurements deviate at higher degrees of deformation.

4.4 Conclusions from experimental study

The results from the bias extension test show that for both materials, the $[45/-45]_s$ layup offers the lowest resistance to deform. For M21, the fibre rotation during deformation coinside with predictions from the PJN theory, while subtantial slip occurs for 977-2. When reducing the fiber layup angle, both materials undergo higher degree of slippage compared to theoretical predictions. The higher degrees of slippage are followed by higher resistance to deformation.
Forming resistance also increaes significantly when adding one third fibre layup angle in the transverse

direction. When the transverse layers are added in the centre of the M21 layup, the fibre rotation is initially governed by the rotation of the $[45/-45]_s$ layers (especially at higher forming temperatures). When placing the transverse layer in-between the two 45/-45 layers, on the other hand, increased slippage has been measured. For 977-2, the degree of slippage is initially similar for both 6-layer configurations and the pure $[45/-45]_s$ laup.

5. Modeling the forming of pre-stacked UD prepreg

Forming modeling is often performed using either kinematic models or a mechanistic approach, where the latter requires significant information on the material to be formed. Kinematic models are based on the PJN theory which assumes that all deformation is taking place through in-plane shear. The yarns are considered inextensible with no thickness and width and locked at cross-over points. The fibres are also assumed straight between cross-over points [4]. However, since the layer is smoothly draped over a tool surface, up-come of wrinkles cannot be seen and in addition there is no slippage over the surface, wherefore each layer is draped separately, ignoring the shear through the thickness and the coupling between layers. Considering the experimental observations done, the latter expels the use of kinematic draping for predicting the material deformation for cross-plied UD prepreg.

A finite element (FE) based software ANIFORM [9] is therefore used in this study. The software is based on the mechanical approach and each ply is modeled as a decoupled continuum shell, meaning that the constitutive model for the in-plane deformation differs from the bending deformation. A reinforced Kelvin-Voigt model is used for the in-plane part, where the matrix consists of an isotropic elastic (spring) material model together with a Newtonian fluid (damper). The fibres are modeled using a linear elastic fibre model, defined with respect to the elements local coordinate system and can be added in an arbitrary initial fibre direction. An orthotropic elastic model is chosen for the bending part, which handles the out-of-plane deformation [9]. The interply prepreg-prepreg and tool-prepreg properties may be modelled using one or a combination of contact models, including viscous friction and Coulomb friction including penalty stiffness.

4.1 Model set up

The material models for the shell representing the ply is calibrated towards the load deformation curves from the bias-extension tests, $[45/-45]_s$ stacking. Further, the prepreg-prepreg interaction is calibrated towards experimental friction test data presented in Ref 2, showing a combination of viscous and Coulomb friction. The software is initially developed for modelling the forming behaviour of thermoplastic matrix composites, wherefore calibration routines are more focused on the hydrodynamic friction behaviour. The model results presented herein primarily aims to investigate the feasibility of the software to predict the behaviour of the herein considered material systems, wherefore only one material and temperature is focused on: M21 at forming temperature 85°C.

4.2 Model results and discussion

Fig. 4 shows the results from the calibrated FE model when used to model the load to deformation during bias extension test on M21 at 85°C, $[45/-45]_s$ layup. As can be seen, considering force to deformation the deviation from measurement is large at small deformations, but that measurements and model seem to converge towards the same value at higher deformations. One possible explanation to the deviation is that the measurement used for calibration of the interply friction properties has been performed at a normal force of 53 kPa. In the bias-extension tests, no normal force is applied, wherefore the influence of tack and hydrodynamic friction becomes very large. This may not has been accurately captured at such high normal force. Methods for improved measurements at lower normal forces are currently investigated. Despite the fairly large deviations in load, the model predicts very accurately the fibre rotation following deformation, see Fig. 4, which is very encouraging.

Fig. 5 shows the predictions of the calibrated FE model when used for modelling of the bias extension test of the two different 6-ply layups considered in the experimental part of this paper. As can be seen, the predicted load to deformation is initially better than for the previous $[45/-45]_s$ case. Further, the model enables predicting the difference in load levels in-between the different stacking sequences. Considering the fibre rotation during deformation, the FE model predictions coincide perfectly with the experimental measurements on the $[45/90/-45]_s$ layup. Considering the other layup, $[45/-45/90]_s$, the model predictions does not succeed in predicting that the layup initially rotates according to the PJN theory. This further stresses the need for better calibration data considering interply slippage at zero normal force. However, neglecting the initial error, the model predictions show the same slope, i.e. the same evolution of fibre angle rotation, as seen during experimental tests.

5. Conclusions and outlook

The experimental data presented in this paper shows the deformation behaviour of aerospace graded cross-plied UD prepreg. The results confirm that for some stacking sequences, this material may deform in a similar way to a balanced woven material, but that in most cases, significant slippage occurs. This means that during deformation, both fibre rotation, fibre tow compaction, intraply slippage as well as interply slippage contributes to the deformation resistance of the pre-stacked materials. Which deformation mode dominates is not easy to foresee from only a few experiments. The modelling procedure and software used in this paper shows potential to predict the complex behaviour of cross-plied UD prepreg during in-plane deformation. Improved calibration data is required considering the interply friction resistance, which is currently looked in to. Next steps includes out of plane forming and validation towards full scale experiments, currently performed.

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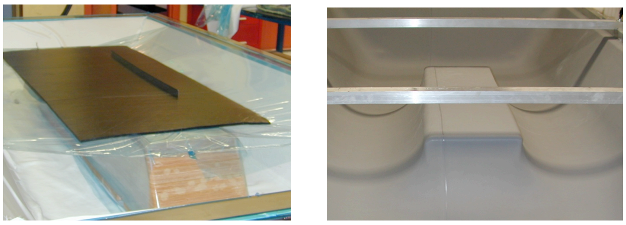
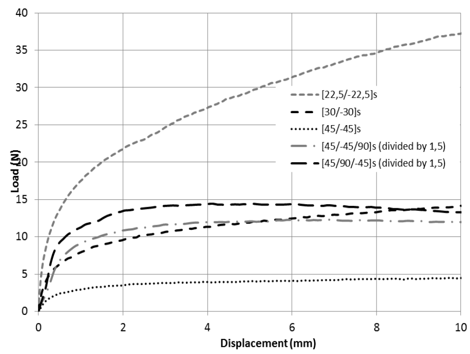


Fig 1. Sheet forming: mould and pre-stacked lamina (left) and after rubber bag is vacuumed (right).



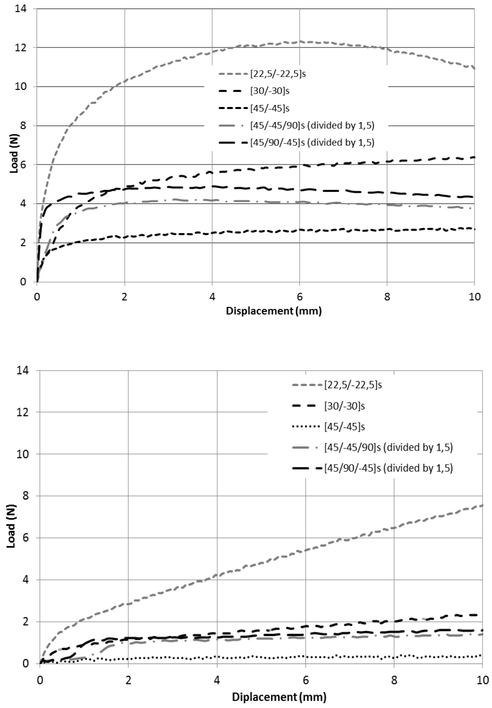


Fig. 2 Load to deformation for different layups: M21 at 60°C (top), M21 at 85°C (middle) and 977-2 (bottom)

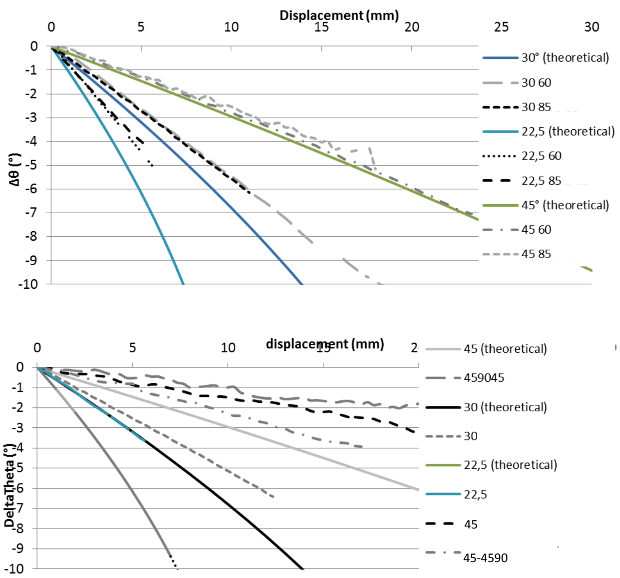


Fig 3. Fibre rotation during bias extention testing for M21 (top) and 977-2 (bottom)

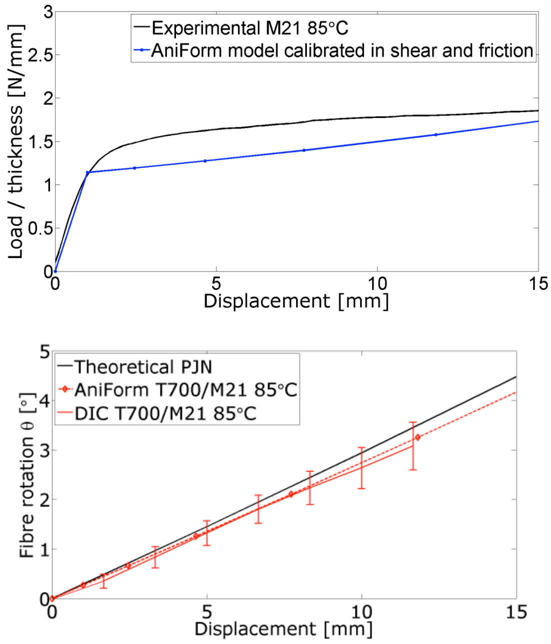


Fig. 4 Modelled versus experimentally measured load to deformation (top) and fibre rotation (bottom) during bias extension test of M21, $[45/-45]_s$, at 85°C.

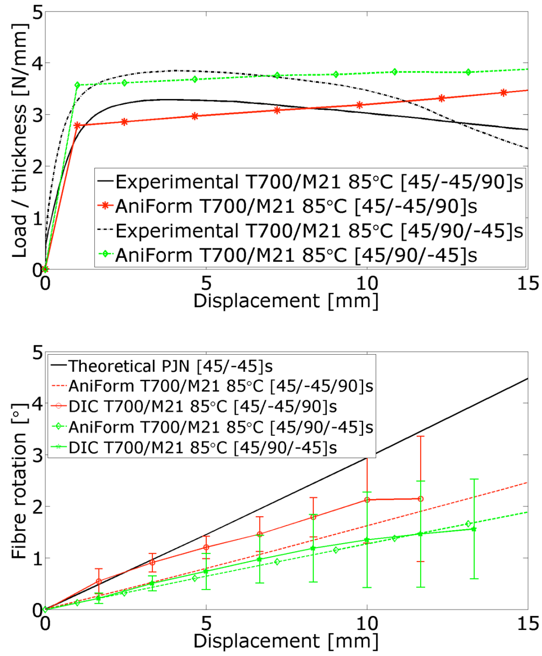


Fig. 5 Modelled versus experimentally measured load to deformation (top) and fibre rotation (bottom) during bias extension test different layups of M21 at 85°C.