IN-PLANE PROPERTIES OF CROSS-PLIED UNIDIRECTIONAL PREPREG

Ylva R. Larberg, Malin Åkermo [Ylva R. Larberg]: larberg@kth.se
Department of Aeronautical and Vehicle Engineering,
Kungliga Tekniska Högskolan (KTH), SE-100 44 Stockholm, Sweden

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Abstract

Sheet forming of thermoset composites is a promising method to achieve reduction in manufacturing time and therefore cost. The behaviour of weaves has been thoroughly investigated and the PJN assumption is widely used. Cross-plied UD prepreg may initially show similar behaviour to weaves; however, the complete deformation is more complex, including slippage. Thus, the forming of cross-plies can offer a possibility of increased drapability compared to woven fabrics, but imposes difficulties in predicting forming limits and final fibre angles.

The work presented herein aims to characterise the in-plane properties of cross-plied UD prepreg with the bias extension test method. Understanding the deformation modes and its limits could reduce the number of iterations from idea to component in production.

The forming of a preplied stack depends on many parameters. The study shows that a higher cross-head rate consequently results in a higher load response. In addition, the type of deformation mode changes due to both speed and temperature.

1 Introduction

Aerospace composite components are known for their high quality and low weight. To achieve these properties, unidirectional (UD) carbon fibre prepreg (preimpregnated fibres) is one of the common choices of material. The manufacturing method still used to a large extent is hand lay-up, i.e. placing each layer of prepreg on a mould by hand. To lower the cost of composite components attempts to reduce manufacturing time are made. A promising manufacturing method for thermoset composites with continuous fibres is sheet forming [1, 4, 9]; a method mostly used for thermoplastics. The process can be described as the forming of planar sheets of preplied laminates into more complex shapes, usually by moulds, in/on tools. The pressure that forces the sheet to deform could be applied by a matched die or a compliant diaphragm, for example. If, in combination with sheet forming, the sheets can by stacked by an automatic tape layer (ATL), the time benefits can be great. Despite some remaining limitations, the method is regarded feasible and the cost savings significant.

Much work has been done within the area of drape properties of weaves [1, 6, 10]. The drape behaviour of woven fabrics is highly shear-dominated and commonly described by the pin-jointed net (PJN) approximation. This approximation was initially proposed by Mack and Taylor [3] thereafter developed and widely used, e.g. [2, 7, 8, 10]. The first assumption made is that the fibres are considered to be inextensible. In addition, the cross-over points are not allowed to slip, but can rotate freely. Implicitly this results in that there is no resistance to lateral bending, i.e. the fibre can have different angles on each side of a cross-over. For weaves, a shear locking angle can be determined, but for cross-plies there is no such obvious limit.

Cross-plied UD prepreg may initially show similar behaviour to woven fabrics and a method to investigate this was proposed by Potter [7]. However, since cross-plies lack the physical links of a weave, the complete deformation is more complex, including slippage. Thus, the forming of cross-plies offers a possibility of increased drapability compared to woven fabrics, but imposes difficulties in predicting forming limits and final fibre angles [8]. Consequently, further work is needed to understand the deformation mechanisms better.

The challenge when forming preplied continuous thermoset prepreg is to induce/force the material to deform in the possible modes while suppressing all failure modes [1]. The common failure mode are fibre misalignment, in-plane fibre buckling, laminate wrinkling and an undesirable change in thickness.

The parameters that can affect the result of sheet forming are many: temperature, forming speed, diaphragm or die properties, stacking sequence, the amount of pressure and its distribution, degree of impregnation, mould surface and of course the geometry of the tools etc.

The aim of this study is to investigate the in-plane properties of stacked UD prepreg through experimental tests. The focus is on finding the deformation mechanisms, especially at an elevated temperature. Furthermore, it aims to find an experimental methodology enabling comparison of the deformability of different cross-plied prepreg systems.

2 Theory

In most drape predictions the reinforcement is assumed to be inextensible. Considering that the matrix (in its uncured state) is so much weaker than the fibres, this can be seen as a valid assumption. The deformation therefore has to take place within the matrix, i.e. between fibre tows and prepreg layers. The known deformation modes for a stack of prepreg with continuous fibres are interply (between layers), intraply (within layers), resin percolation and squeeze flow [5].

In-plane shear can be divided into two parts, intra- and interply shear. To measure intraply properties a picture-frame or a bias extension test can be used. The interply properties can be measured with a “pull-out test” or a “lap shear test” [4], for example. In this study the bias extension test is used.

The bias extension test is an off-axis tensile test that can be used to measure intraply shear properties. To achieve uniform shear a symmetric cross-ply or weaves is located 45° off-axis compared to the tension direction. An idealised test piece is illustrated in Fig. 1 with schematic figures of both undeformed and deformed specimens according to the PJN theory.

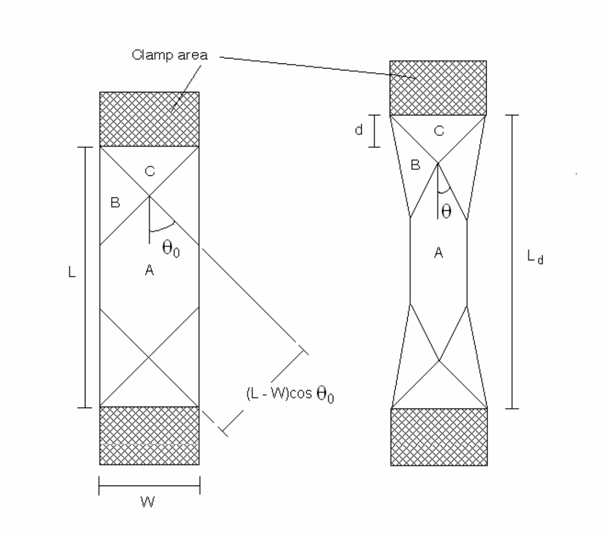

Fig. 1. Bias extension test with idealised shear zones (PJN assumption) for [±45]; undeformed and deformed specimen (illustration inspired by [2, 7])

The PJN theory predicts three different zones within the specimen; A, B and C. Zone A is to the most interesting part, where the shear should be uniform, and a theoretical rotational angle can be calculated according to Eq. 1. [2]. In zone B the shear angle should be half of the angle in zone A. Zone C should remain undeformed. The piece to the right in Fig.1 is deformed a distance *d* and has a total length of L_d:

$$L_d = W + 2(L - W)\cos\theta_0 \cos\theta \qquad (1)$$

The bias extension test allows potential slippage between the layers, due to the sample’s two free edges. This slippage is not possible when using picture-frame; a comparison between bias extension and picture-frame test methods has been made by Lebrun et al. [2]. The picture-frame test starts with a squared specimen clamped at all edges. The idea is to achieve a uniform shear zone when the sample is deformed into a rhomb. The clamped edges force a PJN behaviour on the material and allows no slippage between layers. The method is sensitive to misalignment of fibres, changing the behaviour and causing significantly higher load levels than the intraply shear accounts for. This could lead to a non-repeatable result that is difficult to interpret. A modified version of the test has been developed and has shown to give a more repeatable result [2].

To understand the in-plane deformation properties of cross-plied prepreg one approach is to investigate large shear deformations. This can relate a load response to a deformation mode and also the transitions between them. In this study the bias extension test is used to investigate several potential deformation modes. The experimental behaviour is compared to that predicted by PJN. The aim is to develop a methodology that characterises prepreg systems, which would be a valuable tool for both comparison and modelling.

3 Experimental

3.1 Material

The studied material was Cycom 977-2 with HTS fibre from Cytec; a unidirectional, aerospace graded carbon/epoxy prepreg. The ply thickness was 0.13 mm and a volume fraction fibre of 58 ± 5%.

3.2 Equipment

An Instron 4505 machine equipped with a 5 kN load cell was used for all tests. The software is Cyclic version 7.07.03 from Inersjö Systems AB. The specimen was held in place with pneumatic grips with a clamping force of 1 kN. To control the temperature an environmental chamber surrounded the test set-up. The environmental chamber is specially made by Elastocon AB to suit Instron 4505 and can be used within a temperature interval of 40 to 300°C. To register strain and follow the rotation of fibres, an image processing technique called digital speckle photography (DSP) was used [11]. Aramis (DSP software used) is the system for optical 3D and 2D deformation analysis provided by GOM. The system is suited to measuring three-dimensional deformation and strain with a high accuracy, but due to the glass window covering the environmental chamber only 2D deformation analyses were made. To investigate how temperature and deformation speed influences the load response and the deformation modes a series of bias extension tests was performed.

3.3 Sample preparation

Each specimen consisted of four cross-plied prepreg layers (for most samples $[\pm 45]_s$). To achieve a well controlled thickness the pieces were vacuum consolidated for at least 30 min. Lines for visual inspection of the deformation marked out the middle of the specimen and the borders of the idealised shear zones; see Fig. 2.

For Aramis to be able to register the deformation a stochastic pattern called speckles was applied to the surface of the sample, also seen in Fig. 2.

Fig. 2. Marked and speckled undeformed $[\pm 45]_s$-specimen

All specimens were the same size and had an ungripped sample length L = 250 mm and initial width W = 50 mm. The test piece should have a ratio $L/W > 2$ to experience a relatively uniform shear zone A, according to Wang et al. [10]. The sample tested in this study (shown in Fig. 2.) has a ratio of 5.

The “out-time” (the time out of the freezer) dependency was shown to be significant at room temperature (RT). The load was doubled when comparing test results from day two with tests done day four. To avoid this effect all tests were performed on the third day out of the freezer.

3.4 Test series

The bias extension tests were performed at two different temperatures. The material used in this study has shown acceptable forming properties at RT and that behaviour was therefore tested. The room was controlled to hold 50% humidity and the temperature was around 25°C. The elevated temperature was tested to investigate how it influenced the formability and deformation modes. At a temperature of 70°C the matrix viscosity was expected to offer good forming properties [13]. The influence of an increased strain-rate was tested by performing tests at different cross-head speeds. The cross-head rate interval was between 5 mm/min and 200 mm/min. In addition, the initial cross-ply angle was varied; samples with $[\pm 15]_s$ and $[\pm 30]_s$ were tested. These cross-head rates were chosen to give a comparable strain-rate to the 40 mm/min-case with $[\pm 45]_s$. The calculations were based on the “effective gauge length”, i.e. the length in the fibre direction of the ungripped area [7]. All test combinations are presented in Table 1.

Table 1. Test matrix

Temperature [°C]	Cross-ply angle [°]	Cross-head rates [mm/min]
25	±45	5, 40, 200
	±30	33
	±15	13
70	±45	10, 25, 40, 80, 100
	±30	33
	±15	13

The responding loads were sometimes very low, and therefore the signal was weak. The heavy test set-up made it impossible to change to a more sensitive load cell. Since the distortion was evenly distributed, a filter was used to clean the load response.

4 Results and Discussion

The results are presented as displacement-load curves, which are the only true values recorded for the whole test. The true strain can be calculated based on the deformations registered with the DSP equipment. Large deformations and reflections in the surface of the specimen made it difficult for Aramis to keep track of the sample during test. This resulted in a loss of measuring points, and therefore no strain calculations were possible to obtain after a certain distance (varying between tests). Although measuring points were lost, the series of photos were used to study transitions between deformations modes, especially looking at deformation limits.

The results are presented in three parts: RT, 70°C and a comparison between the two. As can be seen in Table 1., some of the tests were performed at both temperatures, which enabled a comparison between the results.

4.1 Forming at Room Temperature

Since the material can be used when forming at room temperature, in-plane tests were performed in these conditions. To investigate the effect of the deformation speed three different cross-head rates were tested: 5, 40 and 200 mm/min. The strain-rate dependency was clear; the faster the drawing speed the higher the responding load, see Fig. 3.

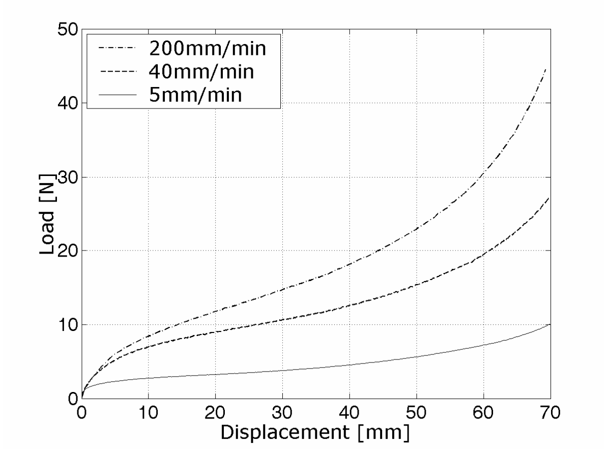

Fig. 3. Different cross-head rates tested at RT

The initial cross-ply angle was varied to investigate how the deformation mode changed. To get a comparable strain-rate the effective gauge length was used to decide the cross-head speed. The zones comparable to the bias test for $[\pm 45]_s$ are of course different; for a smaller angle the interesting zone A will be reduced. In Fig. 4 the strain zones for a $[\pm 15]_s$-specimen are showed. Load-displacement curves for ±15 are presented in the comparative section; 4.3.

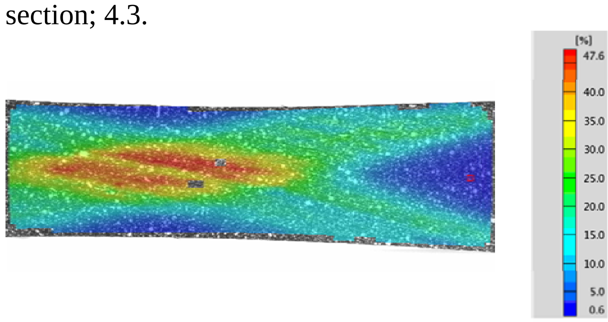

Fig. 4. Strain fields after a deformation of 2.5 mm for an initial cross-ply angle of 15

4.2 Forming at an Elevated Temperature

A well known way of reducing forming loads is to raise the temperature and thereby increase the motion within and between prepreg layers. By raising the temperature to 70°C the willingness to deform in both intra- and interply shear was increased significantly. The responding loads were very low and the limits of deformation were pushed forward by a higher degree of slippage.

Comparing different drawing speeds a strain-rate dependency was seen, as for the samples tested at RT. A higher speed consequently resulted in a higher load response, as seen in Fig. 5. The dominating deformation mode gradually changed from fibre rotation into slippage. At a displacement of approximately 20 mm the initially straight centre line was broken, indicating slippage. When the deformation could no longer take place within the plane the fibre bundles started climbing over each other, here called wrinkling initiation. This phenomenon was seen just before 40 mm of cross-head displacement. This can be seen as a change into a steeper slope in the load curve.

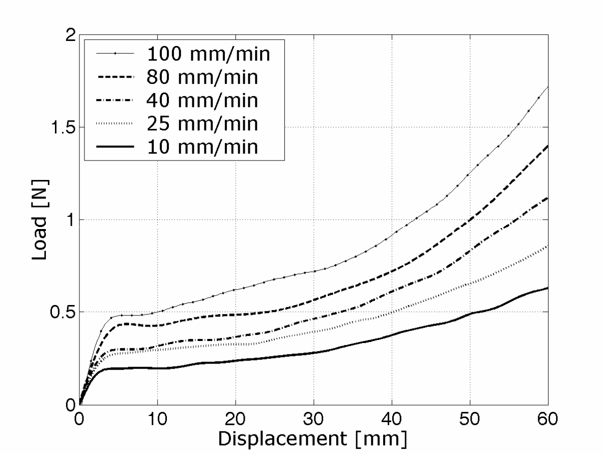

Fig. 5. Different cross-head rates tested at 70°C

At the elevated temperature the intraply slip form bands, between which most of the deformation occurs. The width of the band depended on strain-rate; a slower rate resulted in wider bands, see Fig. 6.

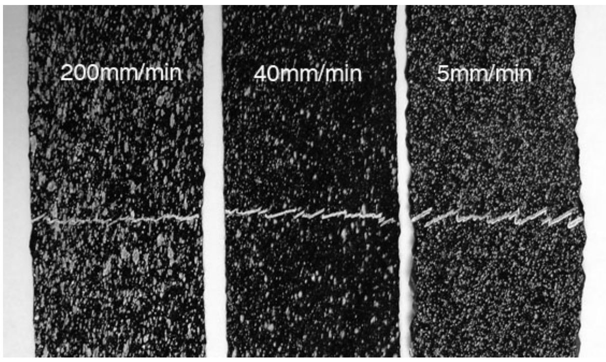

Fig. 6. Different cross-head rates tested at 70°C; the initially straight lines show the difference in slip

This behaviour can be seen when comparing values from the deformation measurements with DSP and a theoretically predicted angle with PJN assumption (Eq. 1.). The result from this comparison can be seen in Fig. 7.

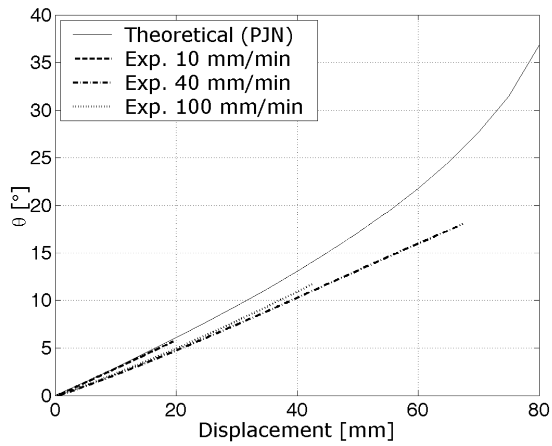

Fig. 7. Theoretical fibre rotation compared with experimental results for $[\pm45]_s$; at 70°C with different cross-head rates

As seen in Fig. 7., the experimentally measured fibre rotation behaves linearly. The slowest test follows the theoretical curve until the measuring points were lost, just before 20 mm of displacement. For the other rates the difference between the theoretical and experimental angle grows as the test continues, this due to slippage.

4.3 Comparison between RT and 70°C

To be able to compare the shape of the curves for the tests at different temperatures, a scaled version of the results from the heated test is presented. The start of deformation modes are marked along the curves. The mechanism at 70°C that is described as wrinkling is the out-of-plane deformation that takes place when the fibre tows climb on top of each other (see Fig. 8.). The wrinkling at RT does not look the same, instead fibre tows expand and is therefore pushed out of the plane, showed in Fig. 8.

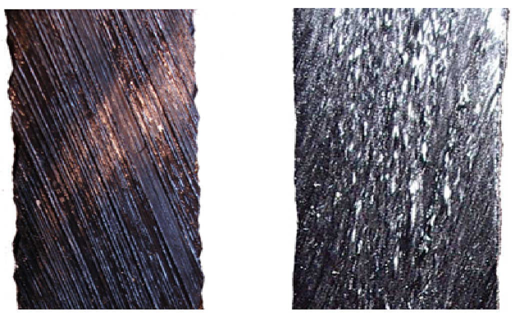

Fig. 8. Comparison of the wrinkling mode at 70°C (to the left) and at RT

Fig. 9. shows load-displacement curves at two different temperatures: RT and 70°C. To enable comparison the values from the 70°C test were multiplied by 20; indicating a significant reduction in load level at the higher temperature.

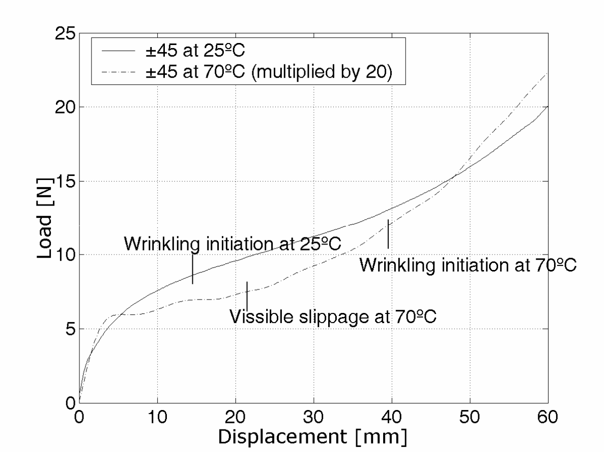

Fig. 9. Typical curves for $[\pm 45]_s$ with a cross-head speed of 40 mm/min, tested at 25 and 70°C (note that load is multiplied by 20 at the elevated temperature)

By inspection of DSP-photos, the transitions between different deformation modes can be identified. The dominating mode during initial deformation was fibre rotation, for both temperatures. For the samples tested in RT, the wrinkling was initiated at approximately 15 mm of displacement. Wrinkling initiation was defined here as the first visible expansion of fibre tows out of the plane. In RT no significant slippage could be seen throughout the tests, but at the elevated temperature slippage was visible to the eye. As defined earlier the slippage was noted when the initially straight line in the middle of the sample started to split up. The curve presenting the result from the 70°C test, slippage occurred just after 20 mm of displacement and wrinkling initiation was seen just before 40 mm of cross-head displacement.

The difference in behaviour for the ±15 cross-plies tested at two temperatures was obvious. As described above the slippage in band formation was seen at 70°C (see Fig.10.). The difference was reflected in the shape of curves, which also can be seen in Fig. 10.

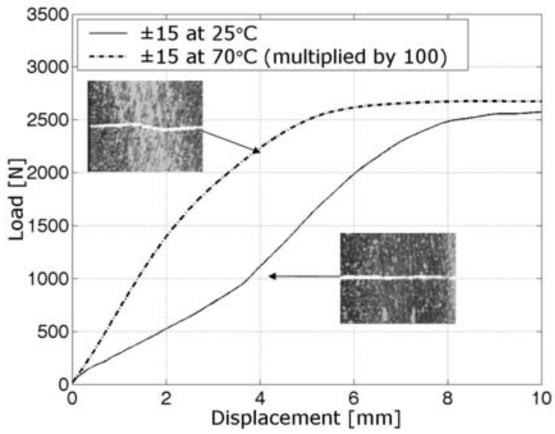

Fig. 10. Typical curves for $[\pm 15]_s$ with a cross-head speed of 13 mm/min, tested at 25 and 70°C (note that load is multiplied by 100 at the elevated temperature)

An increased formability can be seen as a good property, but too much motion of fibres can cause problems. One potential concern with this type of forming is the lack of flow control, which results in unpredictable fibre angles. Even though a component looks flawless it may have experienced total fibre layer wash-outs. This has been seen in components formed with the studied material, Cycom 977-2, at elevated temperature. One way to find flaws is through destructive testing. A material system with well controlled behaviour and visible problem areas would simplify the characterisation.

5 Conclusions

The in-plane forming properties investigated with the bias extension test gave repeatable results. Cold forming has a strong strain-rate dependency, as expected. A higher cross-head rate consequently resulted in a higher load response. The load level changes significantly due to the “out-time” (the time out of the freezer). The fact that the aging of prepreg changes its properties is confirmed by people working with prepreg. The dominating deformation mode during forming depends on the level of deformation, but no or little slip was seen before wrinkling in the room temperature tests.

Although the samples tested at 70°C deformed easily, the strain-rate dependency was present. The increased temperature reduced the viscosity so a larger amount of slippage was seen than in the tests at RT. The ease of forming and an increased slippage correlates well with experience from sheet forming trials.

The ability to measure the properties of a prepreg, and thereby find its deformation limits, offers great possibilities. If the results can be implemented in a virtual material model and the behaviour of stacked prepreg during forming can be captured, many trial and error iterations could be avoided. The results from the bias extensions tests could be used to characterise and compare material systems. To achieve useful results from a simulation, a reliable model of the slippage should be included.

6 Future work

The idea is to use the test results to create and calibrate a material model in a virtual manufacturing method. Other deformation mechanisms should be added and the model used in a full scale forming simulation to find the resulting fibre angles, process limitations and thereby possible tool geometries. Knowing the limits of deformation can help both design engineers and tool designers to reduce the number of iterations in the process of bringing a component into production.

7 Acknowledgements

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