F.E. INVESTIGATION OF THE NON-CRIMP FABRICS COMPRESSIVE AND INTERLAMINAR BEHAVIOURS

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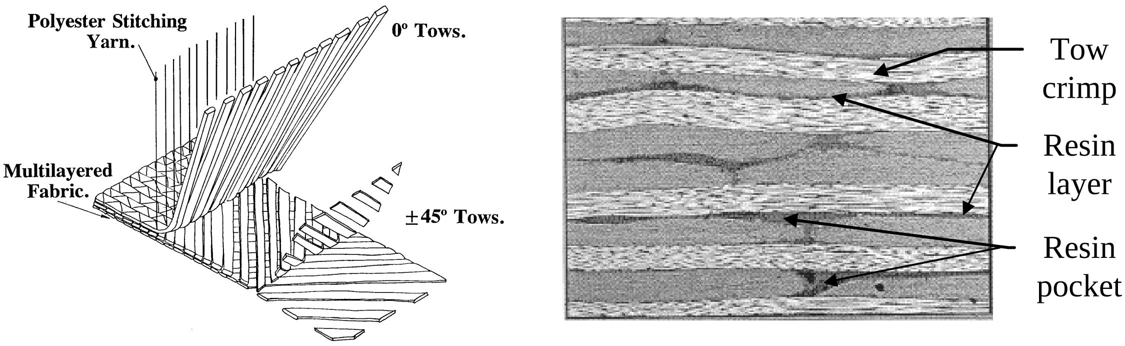
SUMMARY: This work aims first at relating the Non-Crimp Fabrics (NCF) compressive and InterLaminar Shear (ILS) behaviours to the constituents' characteristics. Also manufacturing guidelines to optimise NCF structure against these loadings are derived. The key of this FE modelling is to set the approach at an intermediary scale where geometrical imperfections can be represented along with adequate material non-linearities. This can be achieved only through the proper use of homogeneous equivalent media. A repeating cell is defined across the thickness and along a direction of a biaxial blanket. Results establish that the NCF compressive response is controlled by a mesoscopic instability closely related to the coupling of tows imperfections with the resin non-linear shear behaviour. Under ILS resin controls the NCF response, and indirectly both the presence of resin layers between tows and tow cross-sectional shape are shown to induce shear strain concentrations. Experiments carried out by partners give results which correlate very well with guidelines derived from the present approach.

KEYWORDS: Non-crimp fabrics composites, structure-property relation, non-linear finite element model, compression, interlaminar shear, shear strain concentration.

INTRODUCTION

<u>N</u>on-<u>C</u>rimp <u>F</u>abric (NCF) materials provide an adequate response to the demand for an improvement against damage tolerance in general [1], particularly delamination [2], as well as substantial cost reductions. These composites are obtained by stacking blankets which are typically made up from 2 to 4 layers of fibre stitched together through their thickness (Fig. 1-a). Each layer which can be oriented in several directions is made up of tows of fibres placed side by side. In terms of cost reduction, the improvement comes both from the easier handling/lay-up process and from the use of cheaper tows containing up to 64 k fibres.

Introduction of stitching definitely brings an improvement against delamination. However, it is the change in geometry that the stitching yarn induces which is responsible for this improvement more than the strength of the stitching yarn itself [2]. On the other hand the introduction of stitching has strong drawbacks as it induces heterogeneity at the scale of the tows : resin pockets forming between tows or fibre breakage induced by the penetration of needles. In Ref. 3, various other geometrical imperfections such as tow crimp (Fig. 1) are also observed in the final composite. In this study devoted to the NCF characterisation, a very strong correlation was observed between the experimental strength and some of the parameters measured at the scale of the blanket, especially the tow crimp level and the size of both resin rich pockets and resin layers (Fig. 1-b).



(a) (b)

Fig. 1: Schematic of triaxial NCF manufacturing (a) and example of resulting biaxial NCF stacking (b) (from Ref. [3]) with main imperfections pointed by arrows.

In the literature NCFs are mostly studied from an experimental point of view [2][4] and no established modelling approach exists that relates the NCF properties to the constituents' characteristics. Consequently an investigation of the most critical behaviours of NCF, i.e. compressive and InterLaminar Shear (ILS) strength, is presented here. A finite element modelling is carried out at the blanket scale wherein every medium making up the NCF composites is assumed to be homogeneous. A representative bidimensional unit cell is defined at the blanket scale, taking into account the main geometrical and material parameters at this level likely to affect the overall response.

MESO MODELLING

Mesoscopic repeating cell

From Ref. 3, it is established that the main parameters which were shown experimentally to influence the overall response are at the blanket scale. Also, in [3] a relationship was found to exist between the tow crimp and the parameters of the surrounding layers of tows. This phenomenon called "nesting" (Fig. 2) is induced during cure when tows in one direction (e.g. 0°) tend to "nest" into the gaps left in the complementary direction (resp. 90° in biaxial NCFs). More precisely, the crimp wavelength is set by the spacing of tows in the complementary direction, whereas the misalignment angle (crimp amplitude) depends on the width of the gaps left in this complementary direction. Finally in biaxial NCFs (Fig. 2), the larger the 90° spacing, the larger the 0° crimp wavelength (λ_0), and the wider the 90° gap (larger tow size), the greater the 0° tow maximum misalignment angle (ϕ_0^{max}).

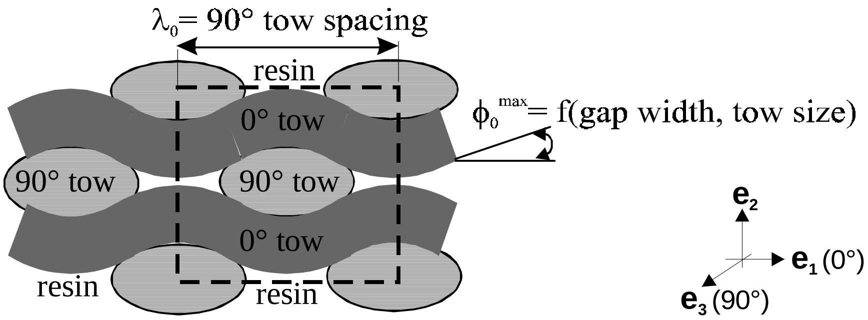


Fig. 2 : schematic of nesting in biaxial NCF and boundaries of the bidimensional repeating cell.

This nesting was showed [2] to very much depend on the stitching tension since when the stitching was removed before curing, the tows could spread and the crimp level was halved. This suggests that the stitching tension might modify the final geometry of the NCF, but no correlation was observed between the NCFs compressive strength and the stitching [2]. By extension, neither the stitching yarn nor its stiffness are accounted for in our model.

Based on this phenomenon of nesting, a bidimensional repeating cell is defined at the blanket scale (Fig. 2) which includes the main imperfections: the tow crimp level and the resin pockets. Under compression only half a wavelength is modelled whereas the antisymmetry of ILS loading requires a wavelength to be represented. Connection of displacements on the cell edges permits simulation of the deformation in a finite medium.

It was decided to focus on the simplest NCF, i.e. biaxial 0°/90°, in order to investigate the basic mechanisms. The crimp level is assumed to be a sine, wavelength and angle of which are measured in Ref. 3. Dimensions of the cell are known from Ref. 3 and dimensions of the tows are calculated from the number of fibres making them up. Then resin pocket dimensions are defined by the room left between 0° and 90° tows. Fibre contents in tows are calculated such that they fit both the areas occupied by the media in the mesh and various material parameters (see Ref. 5 and Ref. 6 for details).

Material and geometry representation

0° tows, 90° tows and resin are assumed to be homogeneous. The non-linear behaviour of the three media is deduced from the same non-linear response of the resin. With simple assumptions on the distribution of stiffness in the media, constitutive laws of the equivalent homogeneous media are expressed with respect to the fibre content. 90° tows and unreinforced material are supposed elasto-plastic, respectively of orthotropic and isotropic type. As for the 0° tows, the knowledge gained in the field of compressive behaviour of homogeneous composites [7][8] lead us to model them very accurately. They are modelled by superimposing beams onto planar elements [8] to represent properly the change in material directions when tows' crimp is increasing. The equivalent homogeneous constitutive law, orthotropic and non-linear in shear, is then rebuilt in a user subroutine implemented in the finite element code ABAQUS® [9].

A generalised plane strain theory is considered to represent the three-dimensional medium with a two-dimensional finite element analysis of a slice of unit thickness. An arc-length path following method is used in order to cope with limit points expected under compression. A baseline case is chosen which corresponds to standard carbon/epoxy T300/914 3k tows (Table 1), with imperfections respectively +2° and –6° for the upper (tow1) and lower tow (tow2) in the cell.

Constituents	Composite (V_f = 0.55)	Dimensions (mm)
E_1^f = 230 GPa	E_1^c = 129 Gpa	0° tow thickness = 0.298
E_2^f = 92 GPa	E_2^c = 9.71 Gpa	90°tow thickness = 0.944
ν_f = 0.25	ν_{12}^c = 0.32	90° tow width = 1.1
E_m = 4.5GPa	ν_{23}^c = 0.45	crimp wavelength = 1.4
ν_m = 0.4		crimp angles = [-8°,+8°]

Table 1 : Mechanical characteristics and dimensions used for computations. Indices "f" and "m" refer respectively to fibres and matrix, and "c" stands for composite.

COMPRESSION

Mesobuckling mechanism

The response of the baseline case is plotted in Fig. 3 (thick line) : after a linear response up to 0.99 GPa, an instability takes place. Experimentally, this point is rarely exceeded as neither a load control nor a displacement control permit to pass this limit point. Therefore we associate the ultimate load to the occurrence of this instability.

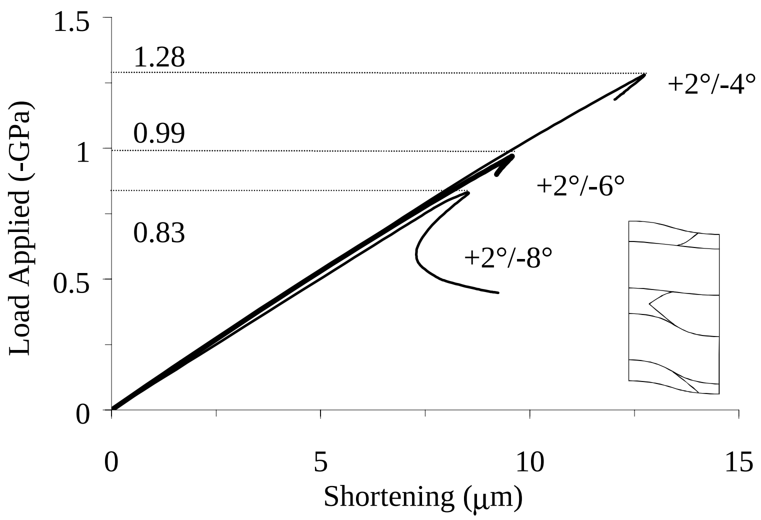


Fig. 3: NCF response for 3 imperfections of tow2 (ϕ_{02}^{max} = -4°,-6°,-8°) in the baseline case.

Initial tow crimp

This overall instability corresponds to the development of a mesoscopic instability of 0° tows. This geometric instability develops along with a sharp increase of shear stresses in resin at the location of the maximum misalignment angle. After the instability there is a localization of these high shear stresses which lead to a shrink of this central zone (sketched in Fig. 3). This phenomenon is very similar to fibre microbuckling. Similarly, there is a strong influence of geometric imperfection (Fig. 3) on the ultimate load. Moreover, as in our case two tows are considered, there is also the influence of the coupling of the imperfection of the two tows on the failure load. In short, not only do the misalignment angles modify the NCF compression strength, but also the larger the difference between the initial crimps the lower the ultimate loads.

Resin behaviour

In microbuckling, it is well known that the resin shear stiffness controls the response. Here we observe very similarly that when changing the resin modulus, ultimate loads change in the same way (Fig. 4). But moreover, increasing the resin modulus by 50% only in 0° tows leads to a improvement of 20% of the ultimate load. Increasing E_m also in resin and 90° tows yield an improvement of 25%. Therefore 80% of the improvement comes from only 0° tows, this reinforces the idea that the resin shear behaviour controls the NCF response through 0° tows mesobuckling.

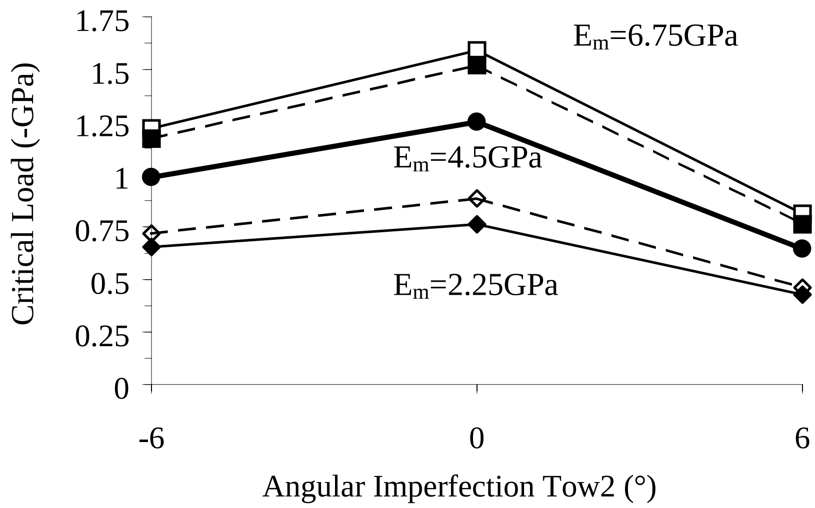


Fig. 4: Critical load versus angular imperfection of tow2 for three resins moduli (E_m = 2.25 Gpa, 4.5 Gpa, 6.75 Gpa). ϕ_{01}^{max} = +2°, ϕ_{02}^{max} = -6°, 0°, +6°. Dotted lines = resin modulus changed in 0° tows only.

Other parameters are shown to have a minor but relevant influence : 90° cross-sectional shape and fibre content. The shape of the 90° tows can be changed by changing stitching tension, such that tows cannot spread during cure and then bunch. We clearly established that 90° tows provide a support against 0° tows mesobuckling. This can lead to a drop of the ultimate load of about 16% if 90° tows do not cover the point of maximum misalignment of 0° tows. As for the fibre an increase in the 0° tow fibre content increases the NCF stiffness, and an increase in both 0° and 90° tows improves both critical stress and critical strain.

INTERLAMINAR SHEAR

As it clearly appears in Fig. 5, the NCF response under ILS loading is very close to the one of a classical unidirectional ply. NCF behave roughly as a stacking of soft and hard layers, as it can be seen on the sketch pictured in Fig. 5. Also, the resin yield stress sets undoubtedly the limit load which NCF can undergo.

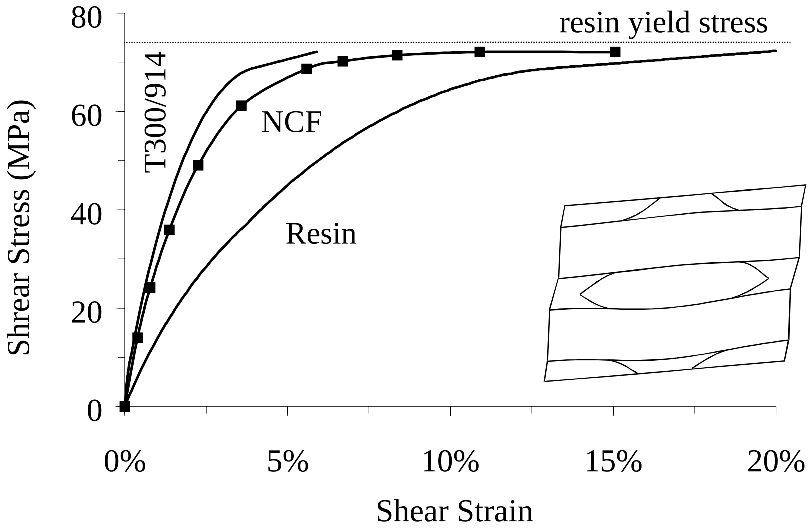


Fig. 5 : Response for the baseline case, resin and 0° tows : shear strain versus shear stress.

One can observe that unlike under compression no instability occurs, but the response is limited by the resin yield stress which is reached in the cell. Consequently the influence of 0° tow misalignment is not relevant under this loading. As for the fibre content, its change modifies only the stiffness but not the limit load. It is a more local observation which reveals that the development of high shear strains controls the NCF response, especially shear strain localization, i.e. gradients over short distances.

These localizations develop especially in resin rich regions and therefore some geometrical characteristics which modify the strain distribution must be observed. A 90° tow shape change can influence the strain distribution as resin pockets are modified indirectly in shape and size. But the largest influence come from both the resin itself and the presence of resin layers between tows (see Fig. 1-b) which provide wide zones for high shear strains to develop as shear loading is transferred from tows to tows through these media. We verify that the thicker the resin layer, the higher the maximum shear strains, and therefore the more likely failure to initiate at lower loads. This is consistent with ILSS experimental measurements from Ref. 3.

On Fig. 6 we can see that increasing the resin modulus leads to an improved stiffness of NCFs. The introduction of 60 µm thick resin layers between tows gives a softer response as high shear strains develop in these narrow bands. Combination of an increased resin modulus with the presence of resin layers yields almost the same response as that of the baseline case. The effect of resin layers on the response is more pronounced for a higher initial resin modulus. This can be explained by the high shear strain localizations which are induced "naturally" in resin pockets for low initial moduli, whereas for higher moduli the introduction of geometric imperfection triggers the development of these localizations. That is to say the use of a tougher resin can be spoiled by the presence of resin layers, the development of which during cure is very difficult to control.

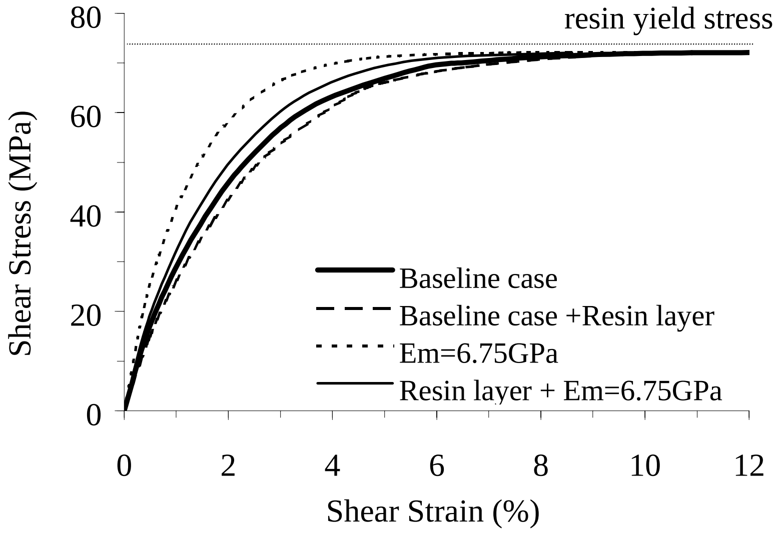


Fig. 6 : Shear responses for the cell with and without resin layer, for 50% increased and genuine resin elastic modulus.

CONCLUSIONS

In this parametric study, we have proposed a model to predict the compressive and ILS response of NCFs. The main result is that the NCF compressive strength is controlled by 0° tow geometrical instability arising at the mesoscopic scale and accompanied by resin shear plastic flow (meso-buckling). Under ILS loading, response is controlled by the development of high shear strain localizations, consequently, the resin behaviour (stiffness and yield stress) along with the presence of resin rich regions (resin pockets, resin layers) are the key parameters.

These results indicate that to improve both NCF compression and ILS strengths, there is a need of having a more homogeneous meso-structure and using a resin with both high modulus and high yield stress. For the geometry, by using a low stitching tension, tows would not bunch, and hence the crimp level would be lower (by limiting nesting) and the 90° tows would spread and thus provide full support to 0° tows. This indication for the stitching tension is confirmed by experimental results [2] which show that in order to improve the NCF compressive strength, the stitch tension should be kept low. As for ILS, the development of high shear strains has to be limited, so from a manufacturing point of view the major difficulty to be addressed is now to limit resin layers.

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