VARIATION IN COMPOSITE TENSILE PROPERTIES DUE TO BIAXIAL DEFORMATION OF KNITTED GLASS FABRICS

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SUMMARY: In the present study, the effect of simultaneously deforming a weft-knit Milano rib fabric on the overall composite tensile properties has been studied for a number of wale-course stretch ratios. It has been found that the tensile modulus, strength and strain-to-failure are all affected to varying degrees by fabric deformation. It is interesting that, contrary to uniaxial deformation, fabrics undergoing simultaneous deformation in both the wale and course directions do not exhibit significant change in the knit structure. Nevertheless, it is believed that the changes in mechanical properties are related to the re-distribution and re-orientation of the fibres resulting from stretching the fabric, thereby altering the relative contents and/or directionality of the fibres in the composites. Further, failure of the knitted composite are concentrated at the highly stressed crossover points of a knit structure, where stretching could unlock or, alternatively, further increase the induced stresses at these point thereby affecting the overall strength of the composite.

KEYWORDS: knitted preforms, textile composites, tensile properties, biaxial deformation, fractography

INTRODUCTION

The use of knitting with advanced fibres, such as glass, carbon and aramid, to produce net-shape or near net-shape preforms has in recent years received increasing interest due to the potential benefits of cost-effective manufacture offered by this technology. Whilst such fabrics are obviously advantageous in reducing production cost by minimising material wastage and reducing labour time, the development of a suitable preform which conforms to prerequisite properties can be a time consuming and, hence, expensive, task. The exercise of deforming a piece of flat knitted fabric over a shaped tool appears to be a good alternative. Previous work has shown that uniaxial deformation to a fabric can alter the tensile [1-4] and, to a lesser degree, compressive [2,5] properties of knitted composites. In the present study, the effects of simultaneously deforming weft-knit Milano rib fabric in the wale and course directions on the longitudinal and transverse composites tensile properties have been investigated.

EXPERIMENTAL

Materials and manufacture

The test panels used for this study were manufactured using Resin Transfer Moulding (RTM) from up to 8 layers of weft-knit Milano rib fabric (see Fig. 1) and Derakane 411-C50 vinyl ester resin, in conjunction with Triganox T-239 catalyst, Conap promoter and 2,4-P inhibitor. An 8-gauge flat bed machine was employed to produce a (undeformed) fabric having nominal areal weight of 762g m^{-2} using 2 × 68tex multi-filament glass fibres.

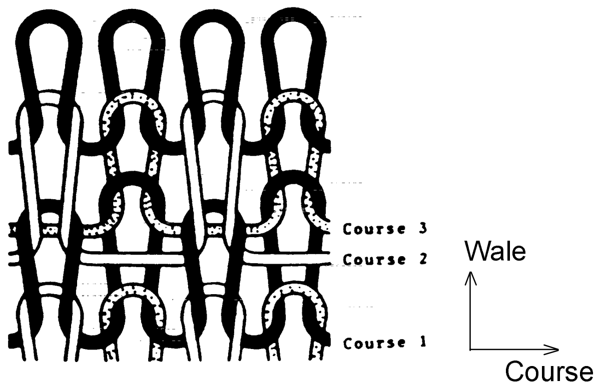


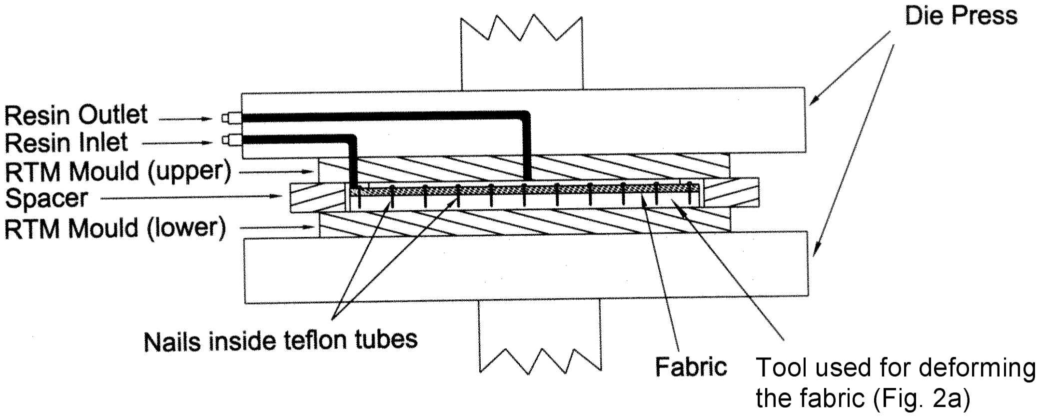
Fig. 1. Schematic of the Milano rib structure.

Table 1. Test matrix.

Deformation (%)	
Wale	Course
0	0
5	10
5	15
10	0
10	5
10	10
10	15
10	20
20	10
20	15

A rig previously used for uniaxial deformation [1,2] was modified to afford systematic (tensile) biaxial deformation to the knitted fabrics (see Fig. 2a). Fabrics were simultaneously deformed along the wale and course axes to different ratios as summarised in Table 1.

(a) Rig used to simultaneously deform the fabric in the wale and course directions prior to consolidation.



(b) Schematic of the RTM tooling used to produced the test panels.

Fig. 2. RTM tooling used to manufacture the knitted composite laminates.

Undeformed and uniaxially deformed fabrics were also considered. The volume fractions (V_f) of the knitted composites were maintained fairly constant at approximately 55%, by varying the number of knitted fabric layers, so as to isolate the effect of V_f on tensile strength and modulus. The dry fabrics were systematically deformed to the required amount in the rig before resin impregnation, during which the rig was incorporated into the RTM mould (see Fig. 2b).

Tensile tests

Straight-sided tensile samples of 200mm × 25mm nominal dimensions were utilised throughout this investigation. Tensile tests were conducted on an Instron 100kN hydraulic mechanical testing machine under a nominal displacement rate of 0.5mm min^{-1}. Specimens were clamped over an area of 40mm × 25mm at each end leaving a gauge length of 120mm. Emery cloth (Screenbak™) was successfully used, instead of end tabs, to ensure failure occurred in the gauge section. Strain was measured over almost the entire specimen gauge length using an MTS 632-12C extensometer modified to a 100mm gauge length. The increased extensometer gauge length ensured that the effects of damage, which occurred uniformly over the entire specimen gauge length, were measured through to final specimen failure. No fewer than 4 specimens were tested for each condition.

Notation

To identify each deformed condition, a notation system containing the alphabets 'W' and 'C', denoting the directions of deformation of wale and course, respectively, that are each followed by an associated numeric which represent the degree of deformation in those directions, is used in this paper. For instance, 'W10C15' represents a sample made from a Milano weft-knit fabric that has undergone 10% and 15% deformation in the wale and course directions, respectively.

RESULTS AND DISCUSSSION

Tensile behaviour

The typical tensile stress-strain behaviour for the knitted composites is illustrated in Fig. 3. The composite basically exhibits linear behaviour at the early stages of loading and then transforms to pseudo-plastic before reaching a maximum stress, followed by a sharp drop in stress. This behaviour has also been reported by other researchers for knitted composites of similar types [2,6]. The stiffness of the composites are calculated from the linear portion of the stress-strain curve, within the strain interval of 0.1% to 0.3%, while the composite strength is defined as the maximum tensile stress attained by the test samples. The ultimate strain is defined as the strain corresponding to the onset of final failure.

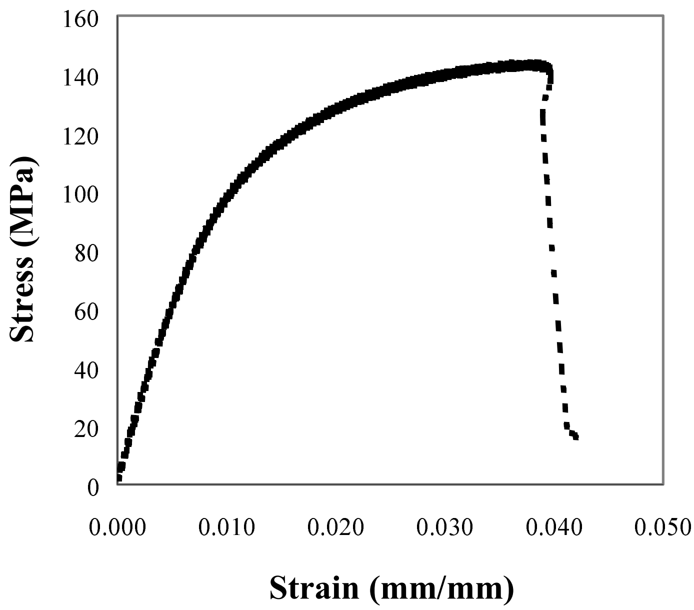


Fig. 3. Representative stress-strain curve of the knitted composites.

Mechanical properties

The influence of deformation on the tensile properties of the knitted composites is presented in Figs. 4 through 6. It will be noted from the charts that the tensile strength (σ_c) and modulus (E_c) of the composite laminates are higher in the wale than in the course direction for all cases under consideration. The composites also have better strain-to-failure (ε_c) in the wale direction, except for the case of W5C15, where the course direction exhibits a somewhat higher ε_c. The superior wale tensile properties are generally believed to be related to a higher proportion of fibre oriented in the wale direction of the composites compared to those oriented in the course direction.

Uniaxial deformation

By comparing W0C0 and W10C0, it is deduced that only the wale σ_c is improved by lightly stretching Milano fabric along the wale axis, but the course σ_c is virtually unaffected. E_c, on

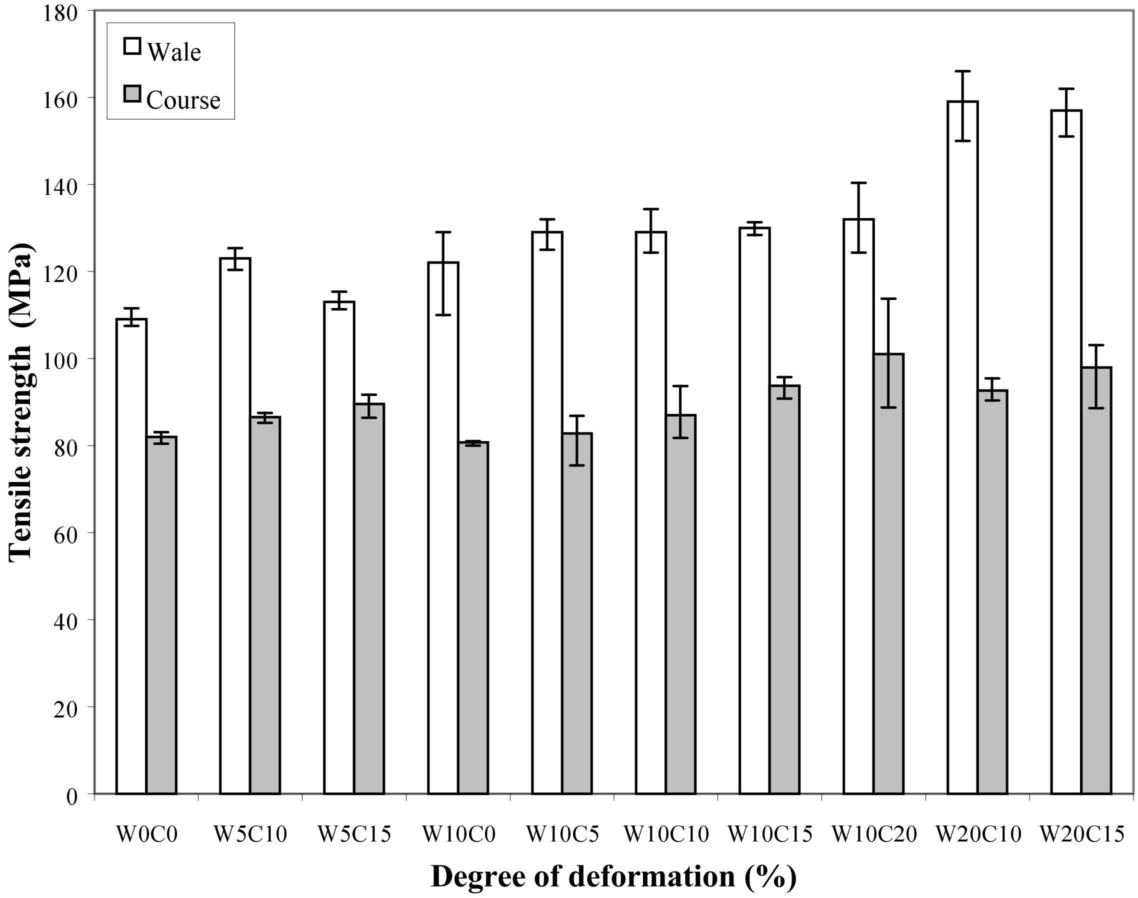


Fig. 4. The effects biaxial fabric deformation on the composite tensile strength.

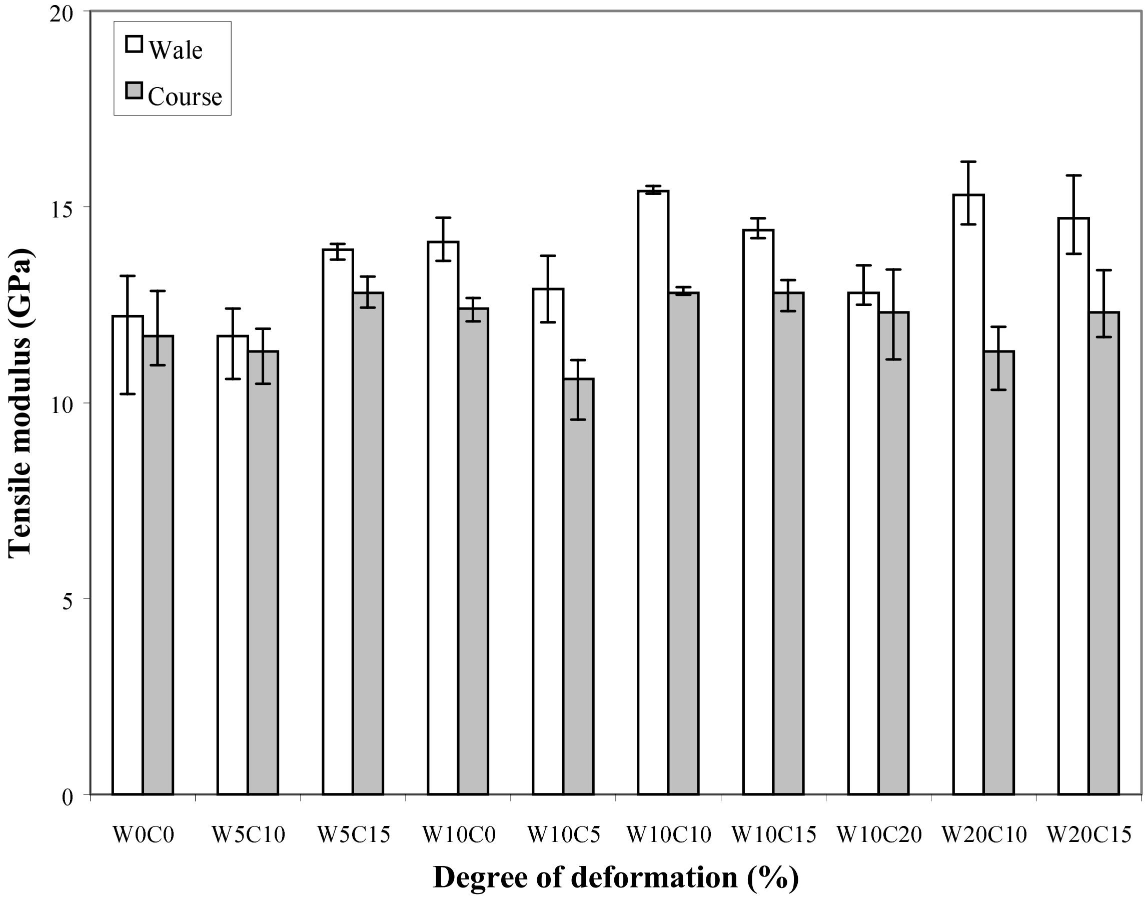


Fig. 5. The effects biaxial fabric deformation on the composite tensile modulus.

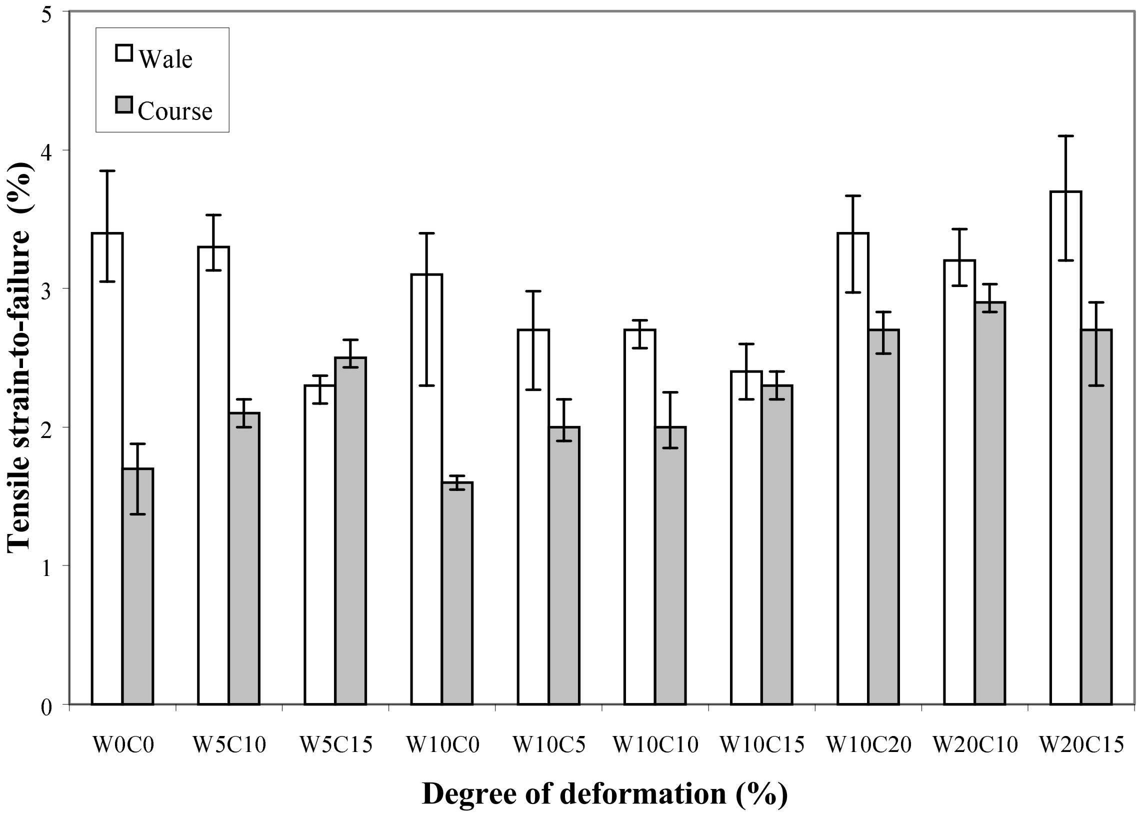


Fig 6. The effects biaxial fabric deformation on the composite ultimate strain.

the other hand, improves in both the wale and course directions with the deformation. This behaviour of σ_c and E_c with respect to wale deformation are consistent with previous work carried out by Leong *et al.* [2] on a similar Milano composite, and can, therefore, be related back to a change in microstructure that has resulted from uniaxial stretching. Only a small deterioration can be detected in ε_c with the 10% wale deformation.

Biaxial deformation

At a particular wale deformed state, increasing the amount of deformation in the course direction increases σ_c along the course axis. For a relatively low degree of wale stretch (of 5%), σ_c along the wale axis appears to be degraded as the course deformation is increased, while for relatively higher wale deformed states (of 10% and 20%), σ_c remained virtually constant.

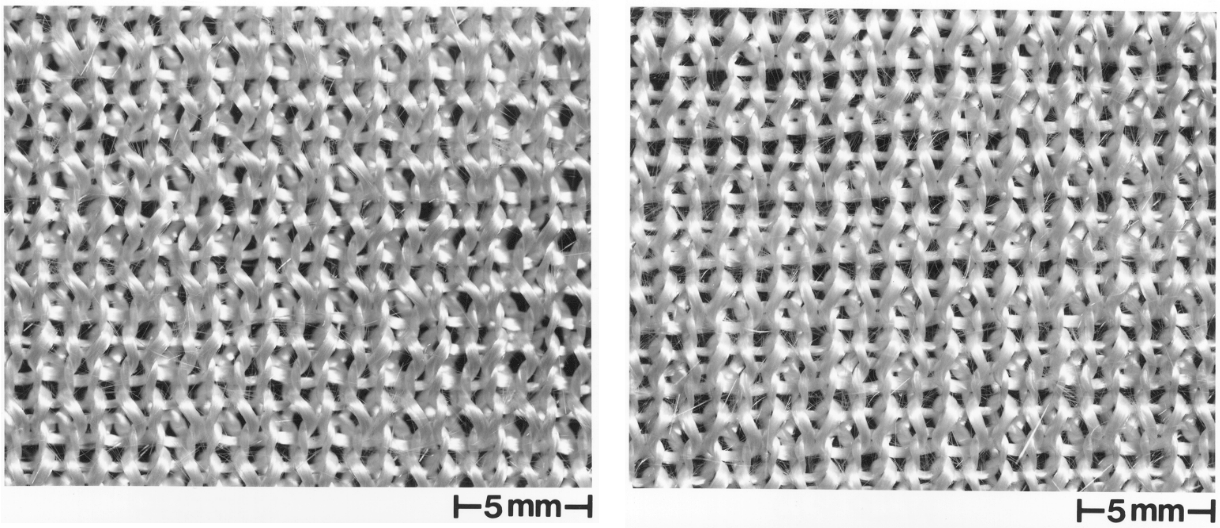
For a constant amount of wale deformation, changes in E_c with course deformation is independent of loading direction. However, these changes appear to be dependent on the amount of wale deformation that the fabric had undergone. When the fabric is lightly stretched (*i.e.* 5%) along the wale axis, E_c is improved with course deformation, but when the fabric is heavily stretched (*i.e.* 20%), E_c is degraded. For the intermediate case (of 10%), E_c appears to be improved initially but then is degraded as the degree of course deformation is increased. The behaviour of ε_c along the course axis with respect to course deformation, at a constant amount of wale deformation, is very similar to that recorded for E_c along the same axis. However, the behaviour of ε_c along the wale axis tends to be the opposite of that of E_c along the wale axis.

At a constant course deformation state, increasing the degree of wale deformation improves σ_c along the wale axis but it only has negligible effect on σ_c along the course axis. E_c on the whole exhibits similar trends to those of σ_c, although not as conclusively. With ε_c, there does not appear to be a trend in how it changes with the degree of wale deformation for either the course or the wale loading directions, although ε_c is clearly affected by fabric deformation.

Microstructure

Figure 7 shows two typical microstructures of biaxially deformed fabrics. It is quite clear from the figure that the knit structures are not significantly altered with biaxial deformation, and this applies across all the cases under investigation. Apparently then, stretching along both the major axes tends to prevent the realisation of a gross change in microstructure of the knitted fabric. This contrasts the observation for the case of uniaxially deformed fabric where distinct changes in knit structure have been recorded and accounted for the changes in mechanical properties of their composites [1,2].

When the knitted fabric is stretched in one direction, the overall distribution and orientation of the fibres are changed [1,2]. If an amount of deformation is then applied in the transverse direction, as in the case of the present work, the overall distribution and orientation of the fibres will again change until an equilibrium state is achieved. The degree of re-distribution and re-orientation is difficult to predict as yet and will depend upon factors such as the friction between contacting fibres at the crossover points, the relative amount of stretch along the two major axes and the manner in which the stretching force is applied. It is the degree of change in fibre loading and/or improved directionality along the wale and course axes with stretching that will dictate E_c, and to some extent σ_c. If friction at crossover points is high and lockup occurs, the induced stresses at those locations may increase to a point where σ_c will be significantly affected. The net effect of all these factors will determine the overall composite tensile properties after fabric deformation.



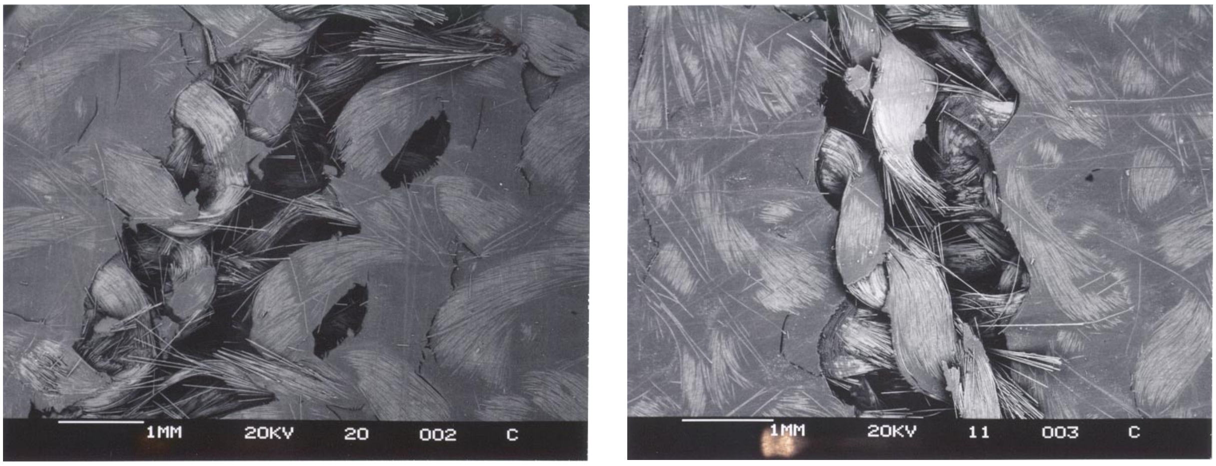
(a) W10C10 (b) W20C15

Fig. 7. The overall knit structure of the Milano architecture is not grossly altered with biaxial deformation of the fabric.

Fracture mechanisms

Regardless of the amount of deformation in the fabric or the loading direction, the first discernible damage in the test specimens was observed to be matrix cracking. This microcracking was audible during testing and the onset of the acoustic signal has been found to approximately coincide with the linear-to-nonlinear transition in the stress-strain behaviour of the composites (see Fig. 3). The matrix cracks appear macroscopically as whitened areas in the test specimens and their numbers multiplied with loading as suggested by the increased intensity and frequency of the acoustic signals with increased loads. It is this progressive accumulation of matrix cracks that accounts for the pseudo-plastic behaviour of the material. This observation is widely reported [1,2,6] and earlier work by Leong *et al.* [6] has revealed that these matrix cracks do not actually span the whole thickness of the specimens but are arrested by the complex array of fibres due to the heavy intermeshing between the different fabric layers.

In the present work, ultimate failure is defined as the point at which there was an appreciable drop in the load-carrying capacity of the test specimen. In most cases when this happens, the specimens were not completely broken but rather the matching fracture surfaces were bridged by a ligament of fabric material. The ultimate failure of the test specimens occurred with the onset of gross fibre fracture, *i.e.* breakage of the first significant group of fibre tows. Scanning electron microscopy further revealed that tensile failure was caused by fibre breakages occurring predominantly at fibre crossover points, although specimens subjected to low amounts of deformation also showed signs of failure at sinker loops which coincide with cross-sections of minimum fibre content (see Figs. 8 and 9).



(a) (b)

Fig. 8. Scanning electron micrographs showing typical tensile failure for a lightly deformed (W10C5) sample. (a) Wale. (b) Course.

(a) (b)

Fig. 9. Scanning electron micrographs showing typical tensile failure for a highly deformed (W20C15) sample. (a) Wale. (b) Course.

Finally, regardless of the amount or wale-course combination of fabric deformation, the failure of the test specimens in the wale direction generally occurred in a plane normal to the loading axis whilst failure in the course direction was more inclined to be at an angled plane of approximately 20º to 45º. Closer examination revealed that the angular nature of the fracture plane was due to fibre breakages occurring across several (in some cases up to 7) adjacent wales of loops.

SUMMARY AND CONCLUSIONS

In the present study, the effect of simultaneously deforming a weft-knit Milano rib fabric on the overall composite tensile properties has been studied for a number of wale-course stretch ratios. It has been found that the tensile modulus, strength and strain-to-failure are all affected to varying degrees by fabric deformation. At a constant amount of wale deformation, the changes in modulus and ultimate strain with course deformation are dependent upon the amount of wale deformation. This is also true for the case of strength along the wale axis but strength along the course axis is improved with course deformation irrespective of how much the fabric is stretched in the wale direction. At a constant amount of course deformation, both modulus and strength along the wale axis show signs of improvement with wale deformation, but are relatively unaffected along the course axis. Whilst the ultimate strain at a constant amount of course deformation is affected by increasing the degree of wale deformation, it is not obvious that there is a trend to it.

It is interesting that, contrary to uniaxial deformation, fabrics undergoing simultaneous deformation in both the wale and course directions do not exhibit significant changes in the knit structure. Re-distribution and re-orientation of the fibres will nevertheless result from stretching the fabric, thereby altering the relative contents and/or directionality of the fibres in the composites and, hence, the composite mechanical properties. Further, failure of the knitted composite is concentrated at the highly stressed crossover points in the fabric, where stretching could unlock or, alternatively, further increase the induced stresses at these points which consequently would affect the overall strength of the composite.

This work highlights the importance of controlling the amount and even distribution of stretch in a knitted fabric during preforming to ensure that the actual composite tensile properties do not deviate too much from expected values, and that the amount of hard and soft spots in the composite component are kept to a minimum, respectively. A better understanding of the manner in which knitted fabrics behave when subjected to deformation will not only assist the designer account for any anomalies due to preforming, it will also pave the way for the development of more accurate predictive tools.

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