MEASUREMENT OF THE LOCAL FIBRE STRAIN DISTRIBUTIONS IN WOVEN COMPOSITES

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SUMMARY: Woven composites have received increasing attention from the composites industry over the past 20 years. Understanding of microscopic deformation mechanics is essential to a full understanding of the macroscopic mechanical properties of composites. Using Raman Spectroscopy [1], it is possible to measure strain distribution along a single fibre within an optically transparent matrix. This method has been extended to woven fabric composites [2,3]. One-dimensional strain distributions have been measured along the centre of the one repeat unit in a variety of woven aramid/epoxy composites. The local strain distributions have been measured at several levels of overall strain. Subsequently, two-dimensional distributions of strain [4] have been built up by taking several parallel linear strain distributions across single sections of fibres in the woven structure. These findings will help in the understanding of macroscopic deformation processes in woven fabric composites.

KEYWORDS: Woven Fabric Composites, Aramid Fibres, Raman Spectrocopy

INTRODUCTION

Textile composites have been widely used in advanced structures in aerospace, automobile and marine industries, because of the ease of fabrication [5,6] and low cost of production along with favorable mechanical properties [7]. Woven fabric composites are probably by far the most widely used form of textile composites in structural applications. They are produced principally by interlacing two or more yarn systems at right angles and exhibit good stability in the warp and filling directions.

Over recent years one of the most exciting developments in polymer science has been in the area of high-performance fibres such as aromatic polyamide (aramid). The fibres exhibit an excellence in mechanical properties owing to highly degree of molecular orientation achieved through the spinning of liquid crystalline solutions of inherently stiff molecules such as poly(p-phenylene terephthalamide) (PPTA) [8,9].

Raman spectroscopy is a very powerful tool in investigating the deformation of high performance rigid-rod fibres such as carbon fibres, aromatic polyamide (aramid) fibres, PBO fibres [10,11], etc. It is also possible to analyse the micro-mechanical properties in woven composites as well as unidirectional laminate composites.

EXPERIMENTAL

Materials

The 5-harness satin weave composites used in this study were supplied by SP Systems, Structural Polymer Systems Limited, UK. The woven aramid reinforcement, a 5-harness satin weave fabric, is shown in Fig. 1. The resin system is Ampreg 20 with a cure of 16 hours at 50 ^{o}C, which is one of the new generations of wet lay-up laminating resins designed by SP systems.

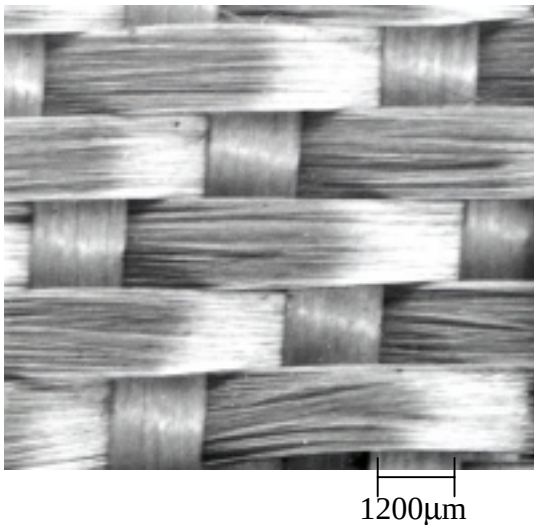

Fig. 1: A photograph of the aramid 5-harness satin weave fabric.

Raman spectroscopy

Raman spectra were obtained from woven composites, using a Renishaw 1000 Raman system using a monochromator with 632.8 nm red line of a 25 mW helium neon laser focused to around 2 μm spot on the surface of the woven composites through a microscope with a ×50 objective lens. A highly sensitive charge-coupled device (CCD) camera was used to collect Raman spectra using an exposure time of 1 s. The Raman band of 1610 cm^{-1} was used to map the fibre strains in the woven composites at different overall applied strain.

Micromechanical Deformation

The woven composite samples were prepared using the method outlined by ASTM D3039. The samples were cut from woven fabric composites using band saw. The dimension of the specimen were 90mm×10mm×0.5mm (length×width×thickness) (see Fig. 2). In order to distribute stress uniformly along the whole specimen while the specimens were subjected to load, aluminum tabs were used to grip each specimen tightly. Subsequently, a resistance strain gauge, of gauge factor 2.065, was attached on the top surface of the specimen using a cold-setting epoxy adhesive.

The mechanical device employed was a 'Minimat' materials straining rig made by Polymer Laboratories, U.K.. A schematic diagram is shown the layout of the experimental apparatus in Fig. 3. The specimen was mounted on the Minimat and then stretched. The diagram of the analysed unit is illustrated in Fig 2.

One-Dimensional (1D) and Two-Dimensional (2D) Strain Mapping

1D strain mapping can be obtained from along the centre of one repeat unit in a variety of woven aramid/epoxy composites. The local strain distributions can be measured in a variety of levels of applied strain determined by a strain gauge. Therefore, it is possible to investigate the local fibre strain distributions as a 2D strain map in woven composites.

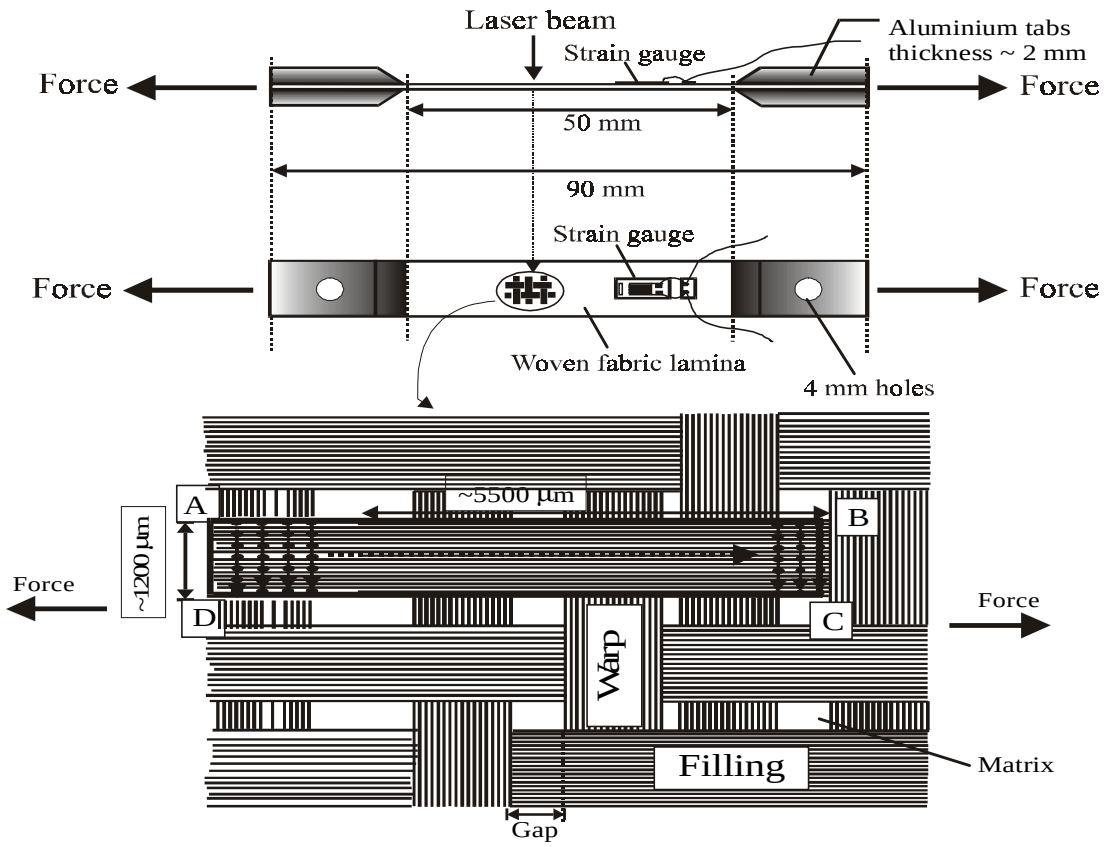

Fig 2: Illustration of two-dimensional strain mapping in 5-harness satin weave fabric lamina. The square ABCD represents the measured area called the analysed unit. Each black spot denotes a measured position.

RESULTS AND DISCUSSION

It has been found that the strongest Raman band, 1610 cm^{-1}, for aramid fibres shifts significantly to a lower wavenumber under the application of a tensile stress [12]. It has also been shown that there is an approximately linear shift in peak position with increasing strain for a single fibre. The band shift rate per unit strain $d\Delta\nu/de$ for the aramid fibres used in this woven composite is -4.30 ± 0.15 cm^{-1}/% strain.

Geometrical structures of the 5-harness satin weave composites can be seen from the optical micrograph of a polished section shown in Fig. 4. Fig. 5 shows the shift and broadening of the distributions of local fibre strain (determined from stress-induced band shifts) for 161 measurements taken from one analysed repeat unit in the woven composite. It can be seen that the spread of distribution of local fibre strain increases with increasing overall strain, e_m,

given by the strain gauge. The reason for the spread is probably due to local variations in fibre structure, and/or imperfections in fibre orientation. Another reason could be the undulation of the strands in both warp and filling directions.

Fig 4: An optical micrograph of polished cross-section of the 5-harness satin weave fabric composite.

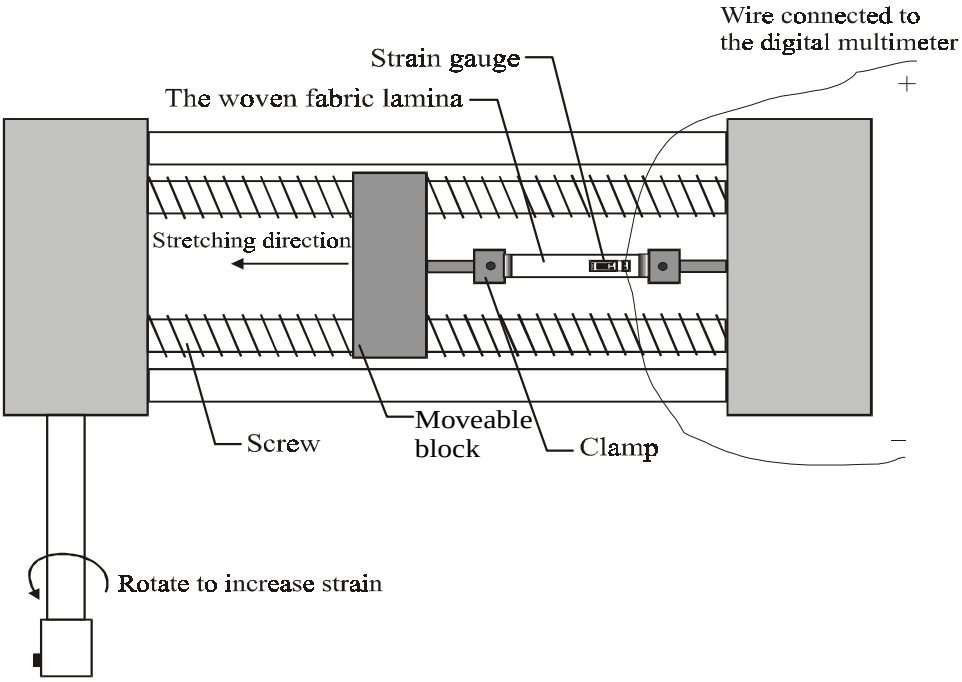

Fig. 3: A diagram of 'Minimat' material straining rig.

Rallis has undertaken similar investigations of the deformation in Kevlar 49 single fibres and Kevlar/epoxy unidirectional composites [3]. He found that there was a larger standard deviation of the distribution for unidirectional composites than for single fibres.

1D variation of local fibre strain along the centre of a analysed cell is shown in Fig. 6. Fig. 7 shows the variation of axial fibre strain with distance along the centre of the repeated pattern in a 5-harness satin weave composite. At composite strain of 0%, there is an overall strain in the woven composite in the order of ~0.15%. It is probably due to residual stresses in the woven composites induced during processing. The current woven composites were cured at 50°C for 5 hours. This might have led to compressive residual stresses in the composite on cooling from the processing temperature [13]. This is because the thermal expansion coefficient of the epoxy resin matrix is usually significantly higher than that of the high-performance fibres. Another reason for residual stresses in present case is that it is very difficult to determine the zero composite strain using the strain gauge, therefore the specimen may have been stretched prior to taking spectra.

Fibre strain increases with increasing overall composite strain shown in Figs. 6 and 7. From the order of composite strain 0.4%, it can be seen very clearly that the variation of axial fibre stresses with distance along the centre of the analysed unit is 'W' shaped. Initially, the fibre strain decreases then increases with distance along the repeat unit until a

maximum is reached at the level of approximately composite strain applied. This plateau is probably because the region can be viewed as a $0^o/90^o$ cross-ply laminate. It should be noted that this 'W' shape is reproducible shown in Fig. 7. Therefore, any analysed unit can be chosen randomly to demonstrate the behaviour of the deformation in the woven composites.

Figs. 8-10 show that two-dimensional distributions of local fibre strain within one repeat cell of the composite subjected to axial tensile loading along the direction of filling. The dimension of the analysed unit is about 1200 μm × 5500 μm (warp width × filling length). It can be seen that the fibres strain at the edge and corners are relatively higher than that at the centre of the analysed unit. This could be because the cross-sectional shape of the filling is lenticular in the transverse direction, leading to a smaller volume fraction of fibres at the edge on the unit as can be seen in Fig 4. It can be expected that domains with a low volume fraction of fibres would bear a higher stress transfer than those consisting of a high volume fraction of fibres, while the specimen was subjected to a axial tensile load. Unfortunately, there is a lack of literature on the micromechanics of woven composites. Many models [14,15] were developed to predict mechanical properties and thermal expansion coefficients of woven composites in the past two decade. The behaviour of fibres in woven composites is being simulated by following deformation of off-axis and curved fibres in model composites. Also, it is being investigated using finite element analysis.

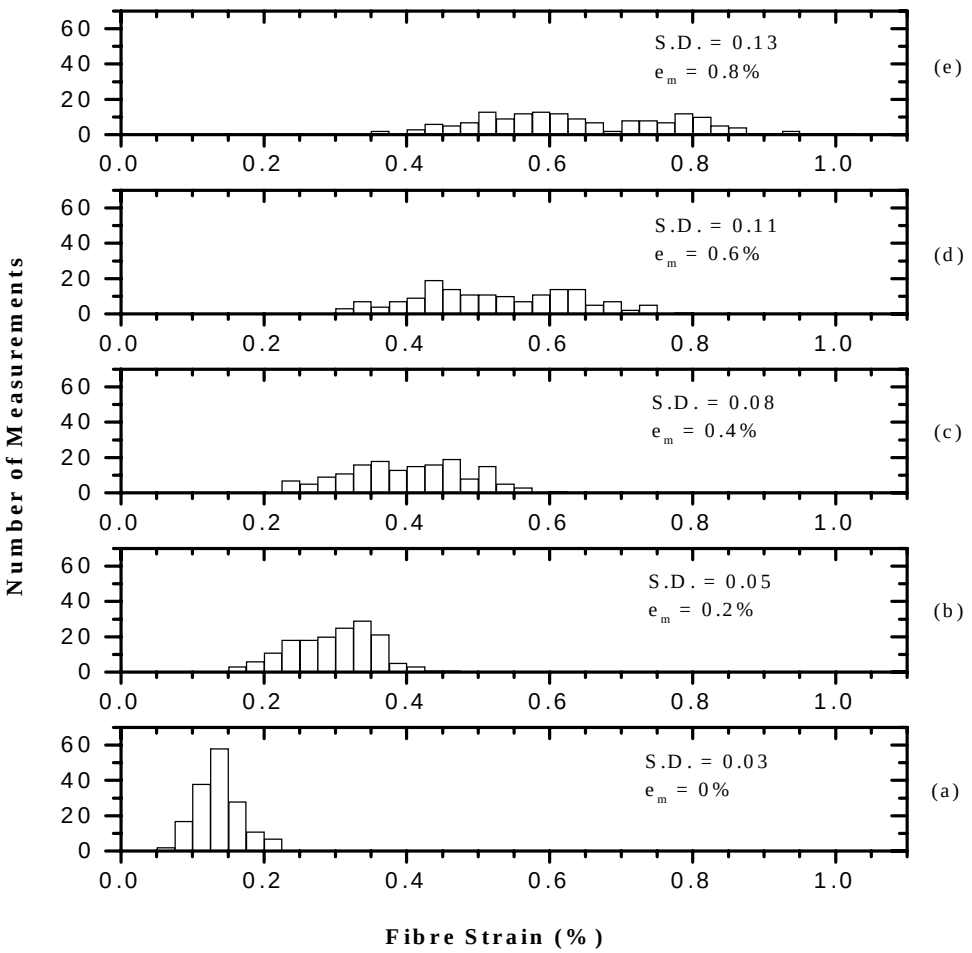

Fig. 5: Histograms showing the local fibre strains for the 5-harness satin weave composites subjected to increasing levels of overall strain (161 measurements). Overall strain: (a) 0% (b) 0.2% (c) 0.4% (d) 0.6% (e) 0.8%.

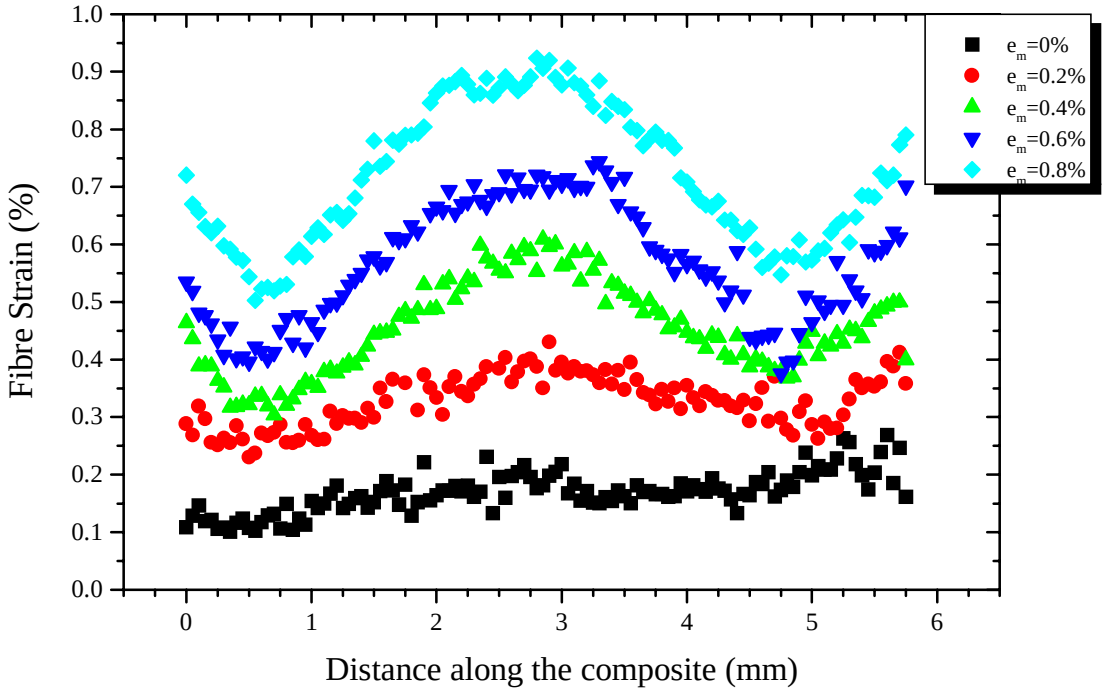

Fig. 6: A variation of axial fibre strain with distance along the centre of one analysed cell at different overall strain levels in the 5-harness satin weave composite.

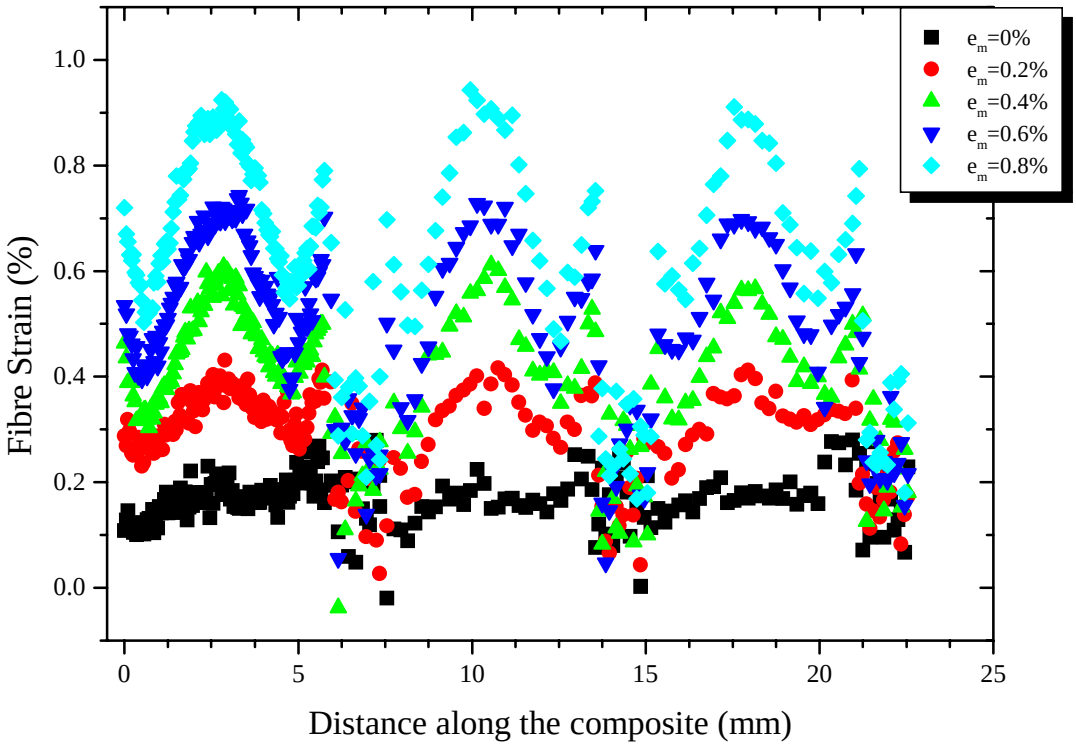

Fig. 7: Variation of axial fibre strain with distance along the centre of the repeating pattern, at five levels of overall strain in the filling direction in the 5-harness satin weave composite.

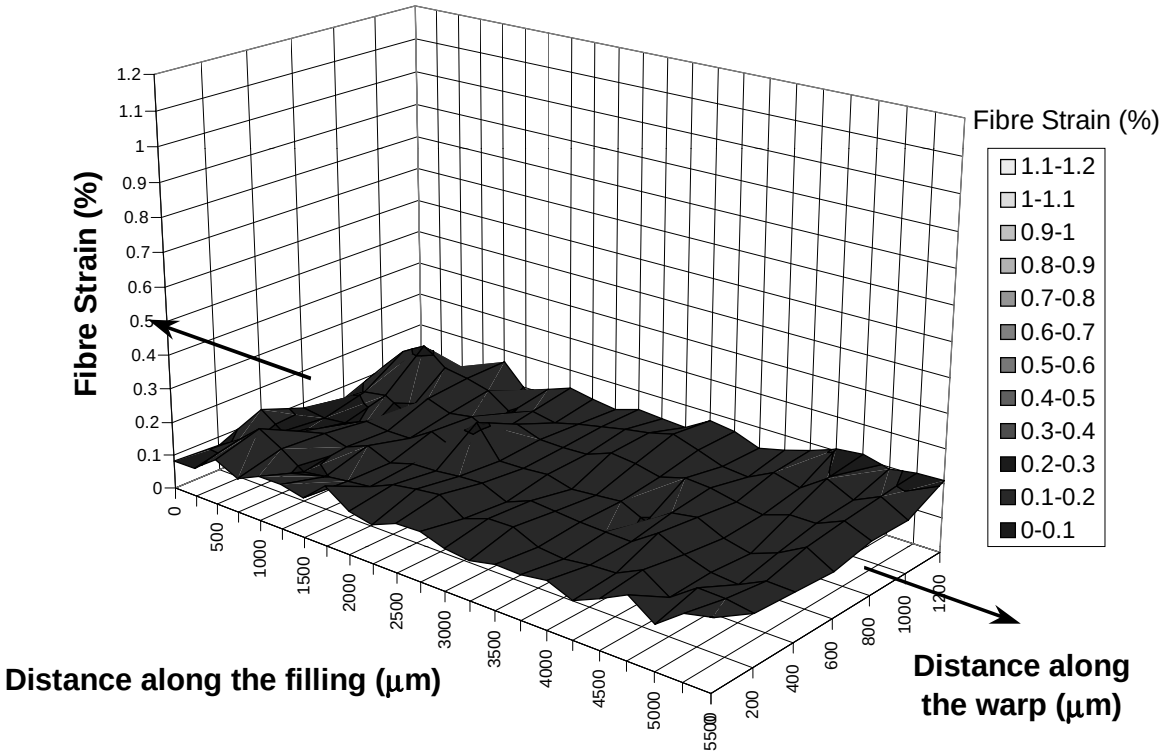

Fig. 8: Two-dimensional distribution of local fibre strains of the 5-harness satin weave fabric composite at overall strain level of 0%. '→' denotes the direction of loading.

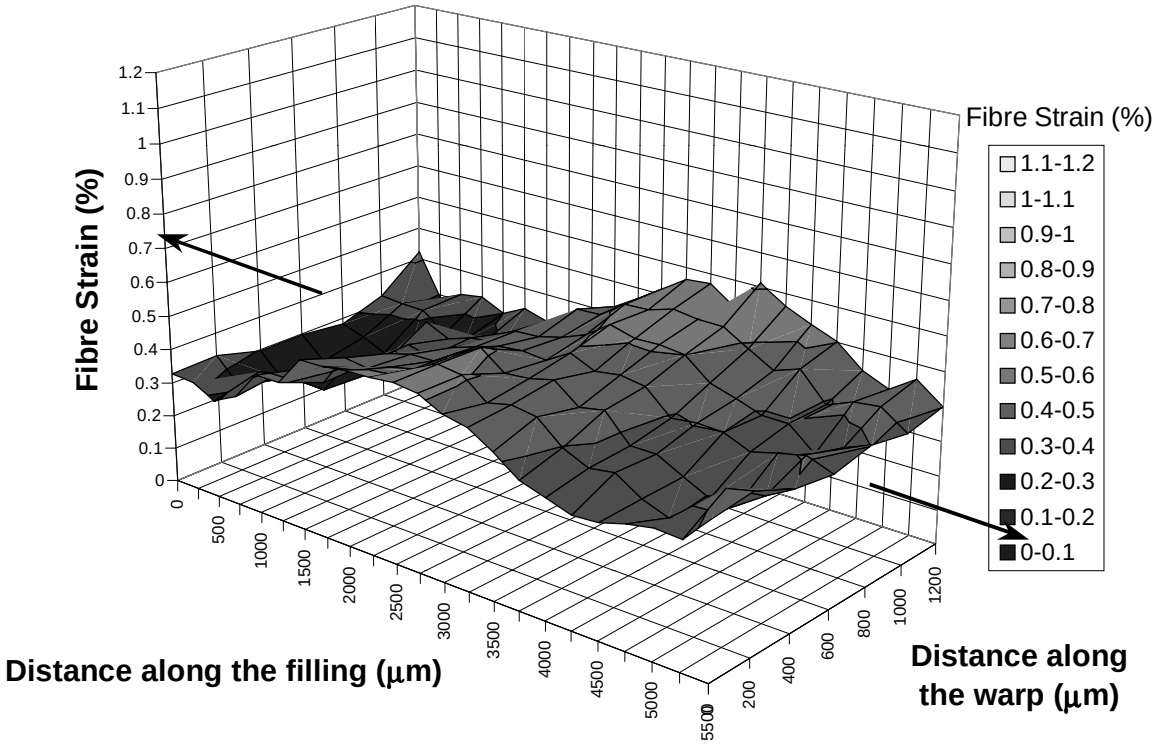

Fig. 9: Two-dimensional distribution of local fibre strains of the 5-harness satin weave fabric composite at overall strain level of 0.4%. '→' denotes the direction of loading.

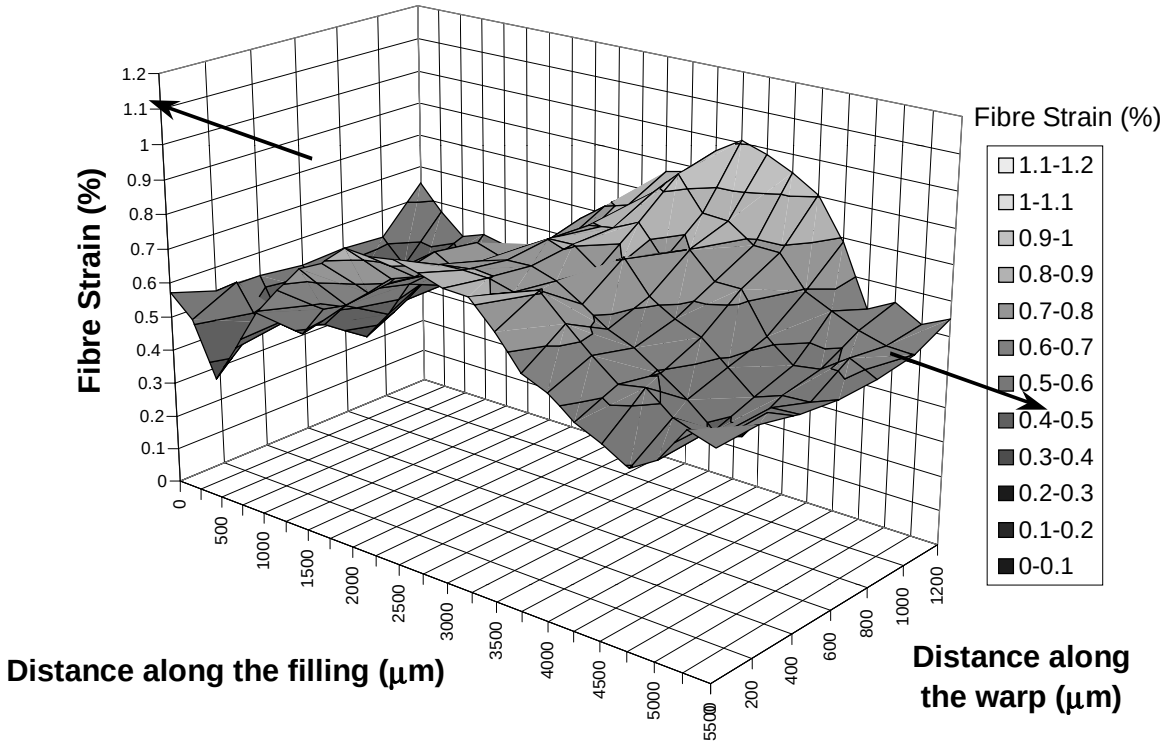

Fig. 10: Two-dimensional distribution of local fibre strains of the 5-harness satin weave fabric composite at overall strain level of 0.8%. '→' denotes the direction of loading.

CONCLUSIONS

The application of Raman spectroscopy to the study of composites has been extended to follow the deformation of micromechanics in the woven composites. One of the most interesting findings has been that it is not only possible to map point-to-point variation of fibre strain in woven fabric composites, but also to measure 2D distribution of local fibre strains. It will be very helpful in the understanding of micromechanics of the deformation of woven composites in the future for this current study to be combined with modelling of the behaviour of woven composites, so that these complicated structural materials can be better understood.

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