TRANSVERSE ELASTICITY PROPERTIES OF A UNIDIRECTIONALLY REINFORCED COMPOSITE WITH A RANDOM FIBRE ARRANGEMENT

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Key words: Transverse elasticity, Uni-directionally reinforced composites, Random fibre arrangement, SEM imaging, Computational modelling, Effective properties.

Summary. The paper deals with the examination of the effective transverse elasticity properties of a uni-directionally-reinforced carbon fibre-polyester composite. The emphasis of the paper is to use the experimentally determined micro-structural irregular arrangement of the fibre distribution in the evaluation of the transverse elasticity properties via computational modelling. The results of the computational modelling are compared with the volume fraction based estimates for the effective transverse properties based on theories that assume regular ordered distributions of fibre arrangements.

1 INTRODUCTION

Fibre-reinforced composites consist of bonded layers of unidirectionally-reinforced sub-elements, which are arranged in such a fashion to derive the optimum deformability and failure characteristics [1-4]. Although purely unidirectionally reinforced composites are seldom used as primary load carrying elements, the transverse mechanical behaviour of such elements can contribute significantly to the development of integrated action required of a composite. Due to the limiting strength of the brittle matrix processes such as matrix fracture with fibre continuity [5, 6] can occur in the composite layer that can have a significant influence in the load carrying capacity of the complete composite. The transverse behaviour of a unidirectionally reinforced element represents the weakest link in the load transfer capabilities of the composite and thus deserves detailed attention, in terms of the evaluation of
its deformability, damage initiation and fracture. Despite this importance, the experimental evaluations of the transverse properties of unidirectionally reinforced materials are rarely conducted and attention is primarily focused on the evaluation of the longitudinal deformability and failure characteristics. In idealized assessments of the transverse effective properties of unidirectionally-reinforced composites, it is invariably assumed that the spatial arrangement of fibres occurs in a regular fashion, which enables the application of the effective elasticity estimates that are usually developed by modelling the mechanics of a representative cell. Experimental observations performed by a number of investigators indicate that the fibre arrangement in unidirectionally reinforced composites is far from regular and that the spatial positions of the fibres are invariably ordered in an irregular pattern. This irregularity in the spatial arrangement of the fibres will influence the estimation of the transverse mechanical properties of the unidirectional composite, in that the transverse effective properties will now be influenced by the Representative Area Element (RAE) of the cross section of the unidirectionally reinforced composite used to represent the composite. This paper deals with the estimation of the transverse elasticity properties of a unidirectionally reinforced composite through the consideration of spatial arrangements of fibres that are determined through Scanning Electron Microscope (SEM) studies conducted on a polyester-carbon fibre reinforced composite. The SEM studies provide visual records of the arrangements of the fibres in the transverse direction which enables the representation of the fibre positions in RAE in a non-ideal fashion as the area is increased in relation to the diameter of the fibre. The SEM data and an image analysis is used to construct the construct a computational model of the RAE, which itself can be randomly oriented. The computational modelling is performed using the general purpose finite element code ABAQUS. The RAE is subjected to homogeneous straining and the resulting strain energy is used to compute the effective transverse elasticity properties of the composite with a non-regular fibre arrangement and to establish the minimum fibre area fraction that will permit the use of the idealized continuum estimates for the transverse elasticity properties of the composite.

2 EXPERIMENTAL DETERMINATION OF FIBRE ARRANGEMENTS

The experimental research program commenced with the study of the fibre arrangement in a carbon fibre reinforced plastic (CFRP) multilaminate plate. The plate used in the research investigations was supplied by a composites products manufacturer in the USA. The supplied multiply plates had different thicknesses, different fibre directions in the individual plies and a relatively constant fibre volume fraction. The properties of the composite in the as supplied condition were provided by the manufacturer.

Figure 1: Sample preparation for the SEM
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and these are as follows:

**Resin:** Specific Gravity 1.2; Tensile Strength 78.6 MPa; Tensile Young’s Modulus 3.1 GPa; Ultimate Tensile Strain 3.4%; Poisson’s ratio 0.35

**Fibre:** Specific Gravity 1.81; Tensile Strength 2450.4 MPa; Tensile Young’s Modulus 224.4 GPa; Ultimate Tensile Strain 1.6%; Poisson’s ratio 0.2

In particular, the objective was to examine the arrangement of fibres in a section of a composite and to focus more specifically on the transverse section of the laminate containing the uni-directional fibre reinforcement. The mapping of the fibre arrangements was performed using a scanning electron microscope. The samples of the multi-ply CFRP multi-laminate CFRP plate of thickness 11.4 mm were cut to coupon sizes measuring 203.2 mm by 25.4 mm. The samples were cast in epoxy that hardened in 24 hours and were first polished using silicon carbide paper (220 grits) (Figure 1). The finishing was done using a finer silicon carbide paper (600 grits). The final polishing operations were performed with diamond solutions (15 μm and 0.05 μm). The polished samples were carbon coated with a layer of thickness less than 1 nm, to eliminate the charging effect of the non-conductive materials used in a SEM environment.

The interaction of electrons and materials in an electron microscope can produce different signals, including secondary electrons, backscatter electrons, Auger electrons, characteristic X-rays, breaking radiation, etc. Two of these signals were used characterize the samples of the composite material. The secondary electron signals were used to obtain information on the fracture topography and backscatter electron signals were used to obtain the chemical information. The theoretical procedures are given in [7]. The fractured samples were observed using secondary electrons. The detector used for this signal is an Everhart-Thornley detector. Secondary electrons are emitted from the surface of the materials. To increase the quality of the signal, the acceleration voltage of the microscope and the probe current are decreased. The tension was set to 2 kV and the current was adjusted to a low value. For each frame, the brightness and contrast were manually adjusted before the image was acquired. The polished samples were observed using back-scattered electrons. The backscattered electron coefficient (i.e. the ratio of backscattered electrons to primary electrons) is a function of the mean atomic number of the emitted signal. The fibres of the composite have a higher mean atomic number than the surrounding matrix; thus the fibres appear brighter on the image than the resin. Better quality backscattered electron images were obtained with a higher acceleration voltage and higher current. The voltage was set to 10 kV and the current was adjusted to a higher value. For each frame, the brightness and contrast were manually adjusted before acquisition of an image. Figure 2 shows the typical fracture pattern and Figure 3 shows typical scan of intact specimens. The image processing toolbox in MATLAB software was used to estimate the fibre volume fraction. All scans were converted into binary black and white images and filter commands were then used to eliminate noise associated with each image. The filtered binary image was used to estimate the fibre volume fraction. The diameter of an average fibre was approximately 8 μm. Some fibres were, however, had a smaller diameter although their proportions in a control region, such as the one shown in Figure 3 did not exceed 5%. The fibre area fraction was estimated by using square sub-regions with dimensions varying 0.5D, 1D, 2D, 3D, ..., nD, where D is the fibre diameter and n depends on the dimensions of the
photographic image. The orientation of the sub-region with respect to global view of the image was selected at 0 and 45 degrees (Fig. 4).
Figure 5 illustrates the variation of the experimentally determined fibre area fraction as a function of the orientation and area of the control region. The fibre area fraction was observed to converge to 66% for the image shown in Fig. 4. Fibres were not uniformly distributed in different layers of the laminated composite. The fibre density had an areal variation.

Figure 5: Estimation of the effective fibre area fraction in orientations normal to the fibre direction representative areas aligned in two different orientations.

A series of tension tests were performed according to ASTM D3039 on single lamina strips measuring 203.2 mm in width and 25.4 mm in effective length, to determine the elastic properties of the composite material. The experimentally determined longitudinal for the Young modulus of a single lamina ($E_1$) was 138.26±5.26 GPA; Poisson’s ratio, $\nu_{12}$ was 0.25±0.01 and tensile strength was 1442.5±110.3 MPa. In this research investigation, we are primarily interested in estimating the transverse effective elasticity properties of the composite from the knowledge of the properties of the constituents and the area fraction of the reinforcing fibres. There are several theoretical relationships that can be used for this purpose and these will be discussed in detail in the complete version of the paper.

3 COMPUTATIONAL MODELLING

An objective of the research is also to use the information of the fibre-configurations derived from SEM scans to develop a model of the composite that can be used to computationally estimate the effective transverse elasticity properties of the composite. The computational modelling was performed using the ABAQUS software. Finite element model of the representative area element was constructed using the images derived from the SEM.
scans and these elemental regions were subjected to suitable homogeneous strains homogenous strain to estimate, through an energy equivalence the effective transverse elasticity properties of the composite (Fig. 6). The upper and lower edges of the model had constraints to ensure homogenous displacement (Second degree of freedom of all nodes in upper and lower edges were fixed to be equal to second degree of freedom of the nodes at the corner). Perfect bonding between matrix and fibres was assumed and damage effects that can result from matrix cracking, debonding at the fibre-matrix interface, transverse cracking of fibres and other defects were not considered in these models. Fibres and matrix were modeled as isotropic materials having elastic constants presented previously.

The finite element discretisation was performed using the CPR8 element, which is an 8-node quadratic element. Very dense meshing was used to discretize model because of the narrow spacing between certain fibres. In the discretization of the entire region 756456 elements were used. The representative area element was subjected to known displacements of 0.1\(\mu\)m along an axis and imposing constraints on the unstressed sides to ensure homogeneity of the deformation. In the shear mode, a the region was constrained to deform in a volume preserving mode and a constant shear strain of 0.1 radians was imposed on the region by prescribing suitable boundary displacements along two opposite edges. Stress and strain distributions resulting from these deformations are shown in Figures 7 and 8. The computational estimates for the elastic constants are as follows: Poisson’s ratio was 0.24; the transverse Young modulus was 8.3 GPa and in plane shear modulus was 5.1 GPa.
4 CONCLUDING REMARKS

The paper describes the problem of the estimation of the transverse elasticity properties of a unidirectional laminate of a multi-ply composite plate using the information obtained form SEM data on fibre arrangements. The important observation is that the distribution of fibres is far from the ideal uniform distributions usually assumed in theoretical developments associated with the modelling of fibre arrangements. These studies show that meaningful estimates of the effective transverse properties of the uni-directionally reinforced composites
can only be defined by considering sub-regions of the composite region where a representative area fraction exists and this area corresponds to a specified value. If this constraint is not applied, the representative area element selected for the modelling will be influenced by either excess of the matrix constituent or the fibre constituent. The results of the computational estimates, the procedures used to compute the effective properties and the comparisons of these results with theoretical estimates will be discussed in detail in a full version of the paper.

Acknowledgements
The work described in the paper was supported by a NSERC Discovery Grant awarded to A.P.S. Selvadurai. The SEM characterization of the composites was done at the Center for the Characterization and Microscopy of Materials, Ecole Polytechnique, Montreal, Quebec, Canada.

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