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Concentrated loading of a fibre-reinforced composite plate: Experimental and computational modeling of boundary fixity

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ABSTRACT

This paper examines the flexural behavior of a locally loaded Carbon Fibre-Reinforced Polymer (CFRP) composite rectangular plate with different edge support conditions. The transversely isotropic elasticity properties of the unidirectionally reinforced laminae were determined experimentally and verified through computational modeling. The assembly of the laminae is used to construct a model of the plate. The layered composite CFRP plate used in the experimental investigation consisted of 11 layers of a polyester matrix reinforced with carbon fibres. The bulk fibre volume fraction in the plate was approximately 61%. The experimental results for the deflected shape of the plate are compared with computational results that take into account large deflections of the plate within the small strain range. It was found that the Representative Area Element (RAE) method developed for estimating the elastic properties of unidirectional fibre reinforced plates provides reliable estimates for the finite element modeling of the composite plate at the macro-scale.

1. Introduction

Fibre-reinforced plates are used quite extensively in various engineering applications, ranging from infrastructure engineering, aerospace engineering, automotive engineering, marine structures and wind energy production [1–4]. In many of these applications, the high strength to weight ratio requirements are satisfied by the fibre reinforced composite.

This paper examines the flexural mechanics problem for a Carbon Fibre Reinforced Polymer (CFRP) laminated rectangular plate that is constrained at the edges. In particular, the edge support conditions were varied to include either (i) complete fixity that can be achieved by clamping the plate between rigid surfaces or (ii) partial fixity that can be achieved by incorporating a deformable rubber-like layer at clamped locations. The elasticity of boundary supports is a research area that has received limited attention, but it is a critical aspect in advanced applications of fibre-reinforced composites, involving connections to metallic and non-metallic components [5,6]. The research also involves computational modeling of the experiments, which takes into consideration large deflection but small strain flexural behavior of the plate.

The accurate theoretical and computational modeling of the mechanical behavior of laminated plates requires the correct specification of their mechanical properties. The composite action of a laminated plate is largely governed by the mechanical properties of the individual layers and these properties are in turn governed by the fibre–matrix constituent properties at the micro-scale (i.e. fibre scale, where the fibre diameter could be approximately 5–10 μm in comparison to the thickness of a plate which could be several millimeters). The simplest theoretical relationships used to estimate the effective properties of a composite are the Voigt and Reuss bounds that assume either the existence of uniform strain (upper bound-Voigt) or uniform stress (lower bound – Reuss) in the individual phases [7]. Improvements to these bounds were provided by a number of investigators; the work of Hashin and Rosen [8] is based on energy principles and the studies by Hill [9,10] are based on the self-consistent scheme. References to recent developments can be found in [11–13]. In a companion study [14], the effective transversely isotropic properties of a unidirectionally fibre-reinforced CFRP composite were investigated using a micro-mechanical evaluation of the irregular fibre arrangements combined with computational simulations. It was shown that the effective transversely isotropic elastic properties of the unidirectionally reinforced composite determined from experimental results together with computational simulations closely matched the results based on the theoretical relationships proposed by Hashin and Rosen [8]. This paper extends the research investigations to the modeling of rectangular laminated plates, consisting of eleven layers of unidirectionally reinforced elements with orthogonal fibre orientations. The plate can experience large deflection behavior during bending. The research also presents results of experimental investigations of the flexural behavior of a multi-laminate composite plate with either fixed or partially fixed boundary conditions, and illustrates

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the need for incorporation of the large flexural deflections of the plate to examine experimental results. The requirement for considering the influence of large deflection behavior is demonstrated through a comparison of computational and experimental results at specified locations of the plate.

2. Plate lay-up and material properties identification

The fibre-reinforced plates were supplied by Aerospace Composite Products (ACP), California, USA. The tested plate measured 460.0 mm × 360.0 mm × 2.4 mm. The composite lay-up was identified using a scanning electron microscopy. The fibre area fraction in each layer was determined using the image processing software available in the MATLAB™ software. The longitudinal elastic properties were measured in the laboratory by conducting tensile tests according to the ASTM D3039 standard, while the transverse properties were estimated using a representative area element-based computational approach.

Scanning Electron Microscopy (SEM): The details of the SEM technique together with MATLAB™ procedure used to image the scans for development of computational representations of the transverse section are described in Selvadurai and Nikopour [14]. Fig. 1 shows the scanned results for the physical arrangement of fibres in the plate. The plate consisted of 11 orthogonally oriented layers with a lay-up of $[(90^{\circ}/0^{\circ})_2, 90^{\circ}, 0^{\circ}, 90^{\circ}, (90^{\circ}/0^{\circ})_2]$ relative to the longitudinal direction of the plate. The fibre volume fraction was approximately 61%.

Longitudinal Elastic Properties: The longitudinal elastic properties of the CFRP specimens were determined from a series of tension tests (ASTM D3039) on fibre-reinforced specimens measuring 200.0 mm × 25.0 mm × 1.4 mm. Two strain gauges, oriented at 0° and 90° to the fibre direction, were installed at the center of the specimens to monitor the longitudinal (1) and transverse (2) strains. These values were then used to calculate one value of Poisson's ratio, (ν_{12}), applicable to the composite. Fig. 2 shows the instrumentation and loading grips used in the tension test. The experimentally determined longitudinal Young's modulus for a single lamina, (E_{11}), was estimated at (138.26 ± 5.26) GPa and Poisson's ratio, ν_{12}, was estimated to be 0.23 ± 0.01. The properties of both the fibre and matrix materials used in the fabrication of the composite plate were provided by the manufacturer and these are listed in Table 1.

Transverse Elastic Properties: The transverse Young's modulus, E_{22}, Poisson's ratio, ν_{23}, and the plane strain shear modulus, G_{23}, were identified using a computational simulation of a two-dimensional plane strain Representative Area Element (RAE). Region B, as shown in Fig. 1, was selected as a representative area, and the finite element model of that area was developed using the ABAQUS™ software. The fibres and the matrix were modeled as isotropic linearly elastic materials with the elastic constants shown in Table 1. It was also assumed that there was perfect bonding between the fibres and matrix. The RAE was subjected to suitable homogeneous strains to estimate, through an energy equivalence, the effective transverse elasticity properties of the composite. Details of the RAE method used to determine each of the transverse elasticity properties (E_{22}, ν_{23}, and G_{23}) of the composite region are given by Selvadurai and Nikopour [14] and Nikopour [15]. Table 2 shows predictions for the transverse elastic constants using the Hashin and Rosen model [8], which does not take into account any irregularity in the fibre arrangement, and the RAE method [14] that considers irregular fibre arrangements.

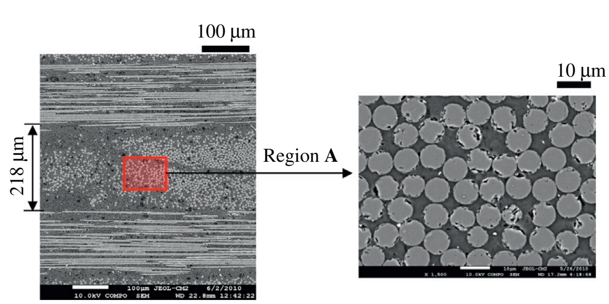

Fig. 1. Fibre arrangement as observed from a scanning electron microscope.

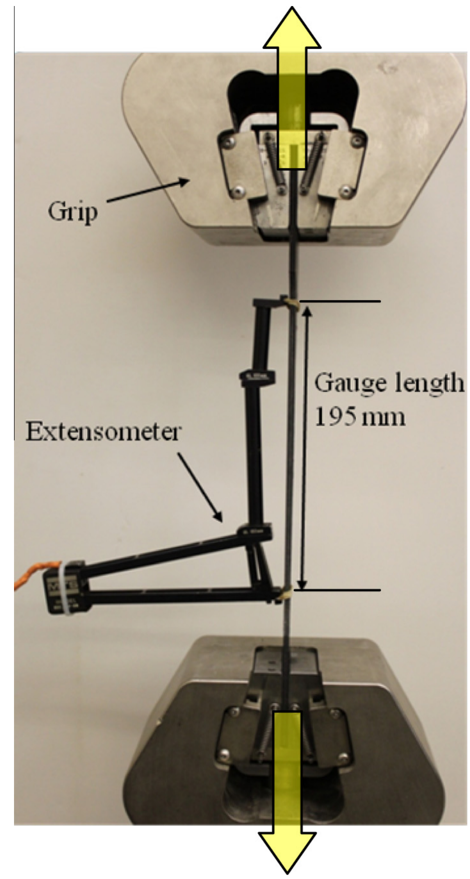

Fig. 2. Tensile test setup.

Table 1
Mechanical properties of resin matrix and fibre.

Property	Specific gravity	Tensile strength (MPa)	Young's modulus (GPa)	Ultimate tensile strain (%)	Poisson's ratio
Resin	1.20	78.6	3.10	3.4	0.35
Fibre	1.81	2450.4	224.40	1.6	0.20

Table 2
Transverse isotropic elasticity properties obtained from Hashin and Rosen [8] and RAE [14] methods.

	Hashin and Rosen	RAE	Percentage difference
E_{11} (GPa)	149.17	146.26	2.0
ν_{12}	0.23	0.23	0.0
E_{22} (GPa)	12.72	12.11	5.0
ν_{23}	0.27	0.29	7.4
G_{23} (GPa)	5.01	4.85	3.3