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Sensitivity analysis of potential tests for determining the interlaminar shear modulus of fibre reinforced composites

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Abstract

A sensitivity analysis using finite element (FE) simulations was conducted as part of an overall attempt to develop a new and robust parameter identification method for determining the interlaminar shear moduli G_{13} and G_{23} of laminated composite materials. It is proposed that the new method will use an integrated experimental and numerical technique. Six different shear and bending tests were investigated numerically using three-dimensional FE models to determine their suitability for this integrated technique. The sensitivity of the potential tests to changes in the different material properties, especially the interlaminar shear moduli, G_{13} and G_{23}, and the elastic modulus in the through-thickness direction, E_3, was determined. It was discovered that several configurations within three of the six potential tests considered are suitable for the new proposed parameter identification method. This is based on the criteria that they are more sensitive to the interlaminar shear moduli than to other material constants. When manufacturing factors were considered, the two most suitable tests were identified for use in the new proposed method.

Keywords: Composite material properties; Interlaminar shear modulus; Sensitivity analysis; Finite element analysis

1. Introduction

Composite materials are becoming increasingly popular in the manufacture of structures and components in the aerospace and defence industries. As a consequence, it is particularly important that such composite structures and components can be manufactured in a cost effective and efficient manner.

The trial and error process often employed in tooling development for manufacturing composite structures and components is a major contributor to unnecessary use of resources. This trial and error process is generally required as there is insufficient material data to allow for accurate predictions of the composite's behaviour during and after the curing process. In many cases, insufficient material data stems from the absence of reliable test methods to provide such information.

Standardised test methods currently exist for most of the in-plane elastic and shear moduli and strength parameters of composite materials [1]. However, test methods for obtaining interlaminar elastic and shear moduli are primitive at best [2]. It is therefore imperative that a robust methodology for determining the interlaminar material properties of composite materials is developed.

In particular, test methods for determining the interlaminar shear moduli, G_{13} and G_{23}, are limited. This is largely attributable to the fact that conventional methods of direct stress and strain measurements cannot be easily adapted for the measurement of interlaminar properties. Utilising these conventional methods for determining the interlaminar shear moduli requires a extremely thick composite coupon to be manufactured, which has proven to be very difficult and costly [3].

The Iosipescu shear test [4,5] is the only standardised procedure that has been used in attempts to determine the interlaminar shear moduli of composites. However, previous investigations have revealed that a pure shear state, which the Iosipescu test relies on, may not be achievable in the test [6–8].

Mespoulet et al. [9] attempted to determine the interlaminar shear moduli using a test similar to that proposed by Post et al. [10]. Two sides of a composite specimen were adhesively bonded to steel rails, and then

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loaded to shear. The specimens were strain-gauged on the two free sides. It was found that failure always occurred through a combination of shear and transverse tension, indicating a pure shear mode was not achieved in the test.

The present authors believe that the interlaminar shear moduli can be determined by applying a parameter identification approach to a designed mechanical test. This approach involves minimising the difference between the experimentally measured and numerically predicted material response (usually displacements) by varying the interlaminar shear moduli. Consequently, the "optimal" interlaminar shear moduli can be determined with a relatively simple test.

For this integrated experimental-numerical technique to be successful, it is important that the measured response in the mechanical test to be used is sensitive to changes in the interlaminar shear moduli while remaining relatively insensitive to changes in the other unknown material properties. In the present paper, six mechanical tests are numerically analysed using the finite element (FE) method. Their suitability for the proposed parameter identification method is determined by considering their sensitivity to changes in different material properties. The effect of the specimen's configuration on the sensitivity is also investigated. Potential test methods with their specimen configuration are proposed based on the analysis.

2. Potential tests and FE models

The suitability of six mechanical tests for the proposed integrated experimental and numerical technique were determined by conducting a sensitivity analysis using a range of FE analysis simulations. The six mechanical tests under investigation were:

- Overlap shear test
- Layered overlap shear test
- Iosipescu shear test
- Three-point bending test
- Cantilever bending test
- Off-axis tensile test

An array of specimen configurations and geometries for each test was considered in order to determine the most suitable specimen dimensions within each test. The different specimen configurations and dimensions for the six potential tests are shown in Table 1.

2.1. Material definition

The test specimens were assumed to be laid-up using a carbon-epoxy plain weave pre-preg material with every ply in the same 0–90° orientation. Table 2 lists the mechanical properties estimated for the model material. To initiate the sensitivity analysis, each of the material properties were varied in turn between the reference value and 130% of this value in 10% increments, as indicated in Table 2. The response of the measurable parameters (to be defined in Section 3) in each of the tests to this change was then recorded.

2.2. Finite element models

FE models were constructed in SDRC-FEMAP for the purpose of this sensitivity analysis. The simulations were then solved using HKS-ABAQUS/Standard and then post-processed again in SDRC-FEMAP.

To capture the response in the through-thickness direction, three-dimensional 8-node linear brick elements (type C3D8 in ABAQUS/Standard) were used for the FE model. Orthotropic material properties were directly applied to the elements as all the layers were in

Table 1
Potential tests considered

Potential test	Configuration	Loading	Geometries	
			Constant (mm)	Variables (mm)
Overlap shear	Unconstrained	Force/Displacement	$L = 10.0$	$h = 0.0, 6.0, 10.0, 12.0, 14.0$
	Load surface constrained	Force	$L = 10.0$	$h = 6.0, 10.0$
	Fully constrained	Force	$L = 10.0$	$h = 6.0, 10.0$
Layered overlap shear	Normal length	Force	$L = 10.0$	$h = 6.0$
	Shortened length	Force	$L = 10.0$	$h = 6.0$
Iosipescu shear	Notched	Force	$a = 40.0$	$b = 10.0, 12.0, 14.0, 16.0, 18.0$
	Un-notched	Force	$a = 40.0$	$b = 10.0, 14.0$
Three-point bend	Normal scale	Force	$S = 130.0$	$t = 10.0, 15.0, 20.0, 25.0$
	Smaller scale	Force	$S = 80.0$	$t = 12.0$
Cantilever bend	Normal scale	Force	$L = 200.0$	$t = 5.0, 10.0, 15.0, 20.0$
Off-axis tensile	Normal scale	Force/Displacement	$L = 150.0$	$\O = 15°, 30°, 45°$