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Material Properties

Coupling coefficients of glass/epoxy laminates under off-axis tensile conditions: Experimental verification

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ABSTRACT

A comprehensive experimental study on the coupling coefficients of unidirectional (UD) and woven fabric glass/epoxy laminates under off-axis tensile loading was conducted in comparison with the theoretical prediction. The capability of the off-axis test to evaluate the elastic constants in the loading direction was reported. Four coupling coefficients were obtained from tests and discussed in comparison with the theoretical prediction. A further comparison of coupling compliance coefficients in compliance matrix was made in order to generalize the influence of off-axis angle on the compliance coefficients. The theoretical prediction agreed well with the experimental data. It is shown that non-monotonic and symmetry phenomena can be observed in the curves of the coupling and compliance coefficients. The results of this experimental study provide a data base of the coupling coefficients of glass/epoxy laminates for engineering application.

1. Introduction

The elastic behaviour of anisotropic solids is an important aspect of engineering. Anisotropic solids are used as structural elements in some modern technology applications. In general, anisotropic materials do not exhibit elastic symmetry, and it is necessary to account for the differences in the mechanical properties in different directions [1–3].

The study of anisotropic elasticity leads to knowledge of the constitutive laws that govern the elastic behaviour of a material and determines the components of the constitutive tensor (or matrix). In a completely anisotropic elastic model, the constitutive tensor possesses 21 unknown constants. Using convenient simplifications, this number can be reduced to nine constants in an orthotropic model, or to two independent material constants in an isotropic model. The orthotropic elastic model requires determination of the following parameters: elastic moduli, shear moduli, and Poisson's ratios, whereas the anisotropic elastic model requires other parameters, such as the coupling coefficients.

As a classical type of anisotropic material, fibre-reinforced composites are well-known for their high weight-specific mechanical properties such as stiffness and strength. Fibre reinforced-composites continue to be used increasingly in automotive and aeronautical structures [4,5]. In these applications, numerous cases involving the design of composite structures show that there is a need for more refined analysis taking into account the constitutive tensor of the material [6–10]. In order to derive the maximum benefit from such advanced anisotropic materials, it is important to understand and predict their constitutive parameters accurately. Many works on mechanical behaviour and failure analysis of fibre-reinforced composites have been so far completed and validated [9–12]. It is also well known that the World Wide Failure Exercises (WWFE-I, II and III) [6–8,13–15], a global comparison of the most prominent failure predictions against common experimental data, revealed scarcity of comparison between theoretical results and test data. Therefore, a paucity of reliable experimental data to establish complete constitutive models considering coupling coefficients for failure theory is still a problem.

The off-axis tensile test on fibre-reinforced composites is a fundamental method which has been successfully employed for a number of years by researchers to characterize the response of these advanced materials. Not only has the test been used to obtain in-plane lamina properties and the related strengths, but also to verify the material-symmetry assumptions of the particular system. The off-axis configuration has also been employed by numerous researchers in determining the in-plane or intralaminar shear modulus. It is an attractive alternative to performing direct torsion tests on thin composite tubes which are more difficult and

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expensive to fabricate. It is also used to acquire the coupling coefficients in the anisotropic elastic model [16,17]. Comparatively, the applicability of the Iosipescu and off-axis test methods for the shear characterization of clear wood was investigated and discussed in the literature [18]. It shows different characteristics between the two methods. A recent new approach for addressing the orthotropy of composite materials taking advantage of full-field measurements and inverse method such as the Virtual Fields Method [19–21] can also be considered for this purpose.

In this work, due to lack of information on the coupling coefficients of fibre-reinforced composites and the practical method of off-axis tests, a comprehensive experimental study of different material configurations of glass/epoxy laminates under off-axis tensile loadings was conducted in comparison with the theoretical prediction. The results of this experimental study provide a data base of the coupling coefficients of glass/epoxy laminates for engineering application.

2. Material and method

2.1. Material

The material under consideration was a glass fibre-reinforced epoxy system. Three types of glass fabrics, i.e. unidirectional (UD), plain and twill fabrics, as shown in Fig. 1, were used, with areal density of 420 g/m^2, 210 g/m^2 and 200 g/m^2, respectively. The matrix material was the epoxy-resin WSR618 system, with benzene dimethylamine used as a resin-curing agent, and butyl phthalate as viscosity additive.

2.2. Specimen preparation

The composite laminates were manufactured by manual layer-by-layer stacking of similar plies. Subsequently, the vacuum bagging technique was used in ambient temperature for plate fabrication for 4 h negative pressure-assisted curing, which is known to reduce typical defects in the laminate such as voids in matrix, delamination between layers or cracks between fibre and matrix. Finally, an aging treatment at 60 °C for 4 h was followed after 24 h of room-temperature cure. Several sets of rectangular specimens were cut from the manufactured panels for off-axis tensile tests, using a water-cooled diamond wheel cutter. The dimensions of the specimens were 250 mm (length) × 25 mm (width) × 2 mm (thickness). Four rectangular aluminium end tabs were bonded to the gripping length (50 mm) of each test specimen. These end tabs, not only reduced the stress concentration from the serrated grips, but also prevented slipping of the test specimen from the grip, where the serration of the grip indented the aluminium tabs and engaged with it [22]. For unidirectional laminates, the panel was cut with seven on-axis and off-axis angles (i.e. $\theta = 0°, 15°, 30°, 45°, 60°, 75°$ and $90°$), while only four on-axis and off-axis angles ($\theta = 0°, 15°, 30°$ and $45°$) were for biaxial plain and twill laminates, due to the same properties in their longitudinal and transverse directions.

2.3. Test procedure

The actual dimensions of manufactured specimens were measured and recorded before testing. The off-axis tensile tests, as shown in Fig. 2, were carried out using a MTS test machine under displacement control following ASTM D3039 [23]. The displacements were measured and recorded by the control system of test machine. The test strain data were measured with three-element strain-gauge rosettes (0°/45°/90°) bonded on the surface of the specimens and recorded using a DH3816 strain indicator. There were five specimens for every type of test.

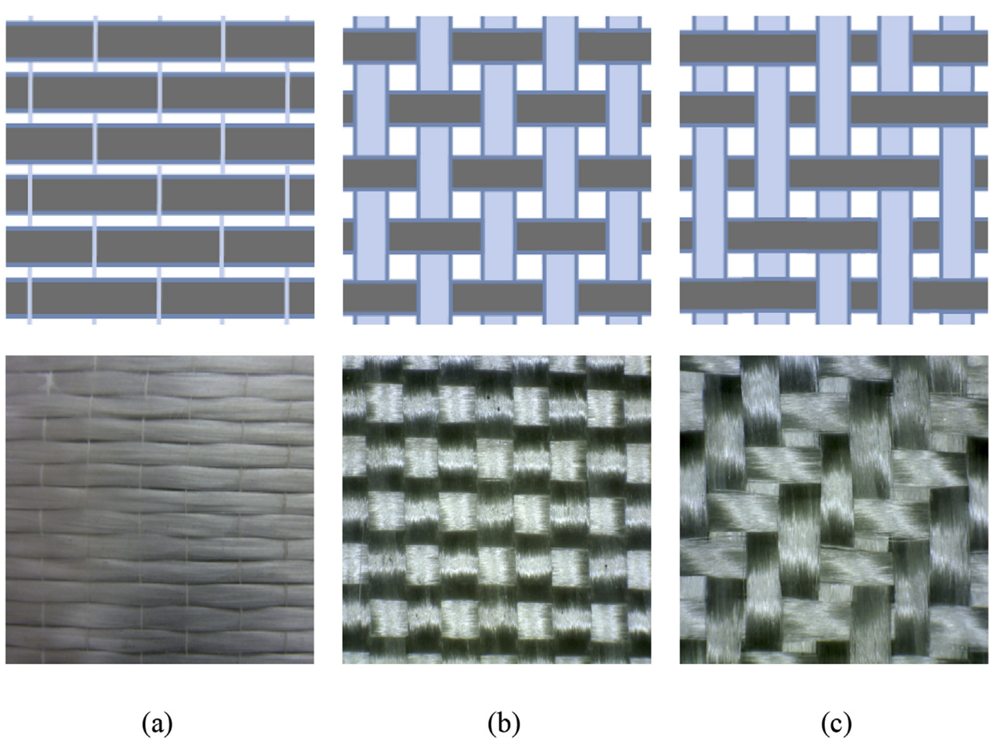

Fig. 1. Type of glass fabric: (a) unidirectional; (b) plain; (c) twill.