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Robustness for unidirectional carbon/glass fibre reinforced hybrid epoxy composites under flexural loading

Chensong Dong *, Mehdi Kalantari, Ian J. Davies

Department of Mechanical Engineering, Curtin University, GPO Box U1987, Perth, Western Australia 6845, Australia

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ABSTRACT

A study on the robustness of unidirectional S-2 glass and T700S carbon fibre reinforced epoxy hybrid composites under flexural loading is presented in this paper. The flexural strengths of various stacking configurations are computed using the Classic Lamination Theory (CLT), and the computed data are fitted to a regression model. With the aid of the developed regression model, robust indices are developed for both flexural strength and specific flexural strength. The concept of robust strength is introduced to address both the strength and robustness criteria, with which a design guideline for robust hybrid composites is given. Simulation studies are conducted to demonstrate the validity of the proposed method.

1. Introduction

Hybrid composites reinforced by more than one type of fibres are of great research interest because they provide a convenient way to achieving tailored material properties. Although carbon fibres are well known for high strength, they have low strain-to-failure because of their high stiffness. Compared to carbon fibres, glass fibres have much higher strain-to-failure due to their lower modulus. From this point, it is possible to increase the strain-to-failure by substitution of carbon fibres for glass fibres.

When considering the mechanical properties of hybrids a general rule of mixtures (RoM) approach may be utilized which quantifies a material property with respect to the volume concentration of its constituents. Many researchers have however noted the existence of hybrid effects in which the material property as predicted by the RoM differs to that observed in reality. A positive or negative hybrid effect is defined as the positive or negative deviation of a certain mechanical property from the RoM behaviour, respectively [1].

Dong et al. [2–5] studied the flexural properties of unidirectional carbon/glass fibre reinforced hybrid epoxy composites using both experiments and finite element analysis (FEA). It is shown partial substitution of carbon fibres for glass fibres on the compressive side results in improved flexural strength, i.e. positive hybrid effect. Dong et al. [6–8] further investigated optimal design of hybrid composites. It is concluded that in order to achieve positive hybrid effects, the fibre volume fraction of the glass/epoxy section needs to be higher than that of the carbon/epoxy section [6,7].

In addition to unidirectional composites, a recent study [9] on the hybrid composites made of carbon and glass woven fabrics showed that both the tensile and compressive strengths showed positive hybrid effects. For short fibre composites, Miwa and Horiba [10] found that the tensile strength of the hybrid composite could be estimated by the additive rule of hybrid mixtures, using the tensile strengths of both composites.

Traditional design of composites is based on a deterministic approach, and a large factor of safety is needed for incorporating the variability of data. A new alternative approach is probabilistic design [11–15], which allows the estimation of reliability and inclusion of stochastic variability [16].

Variability in the performance of composite materials arises mainly from the variability in constituent properties, fibre distribution, structural geometry, loading conditions and also manufacturing process [17]. Fertig et al. [18] shows that microstructural variations, especially volume fraction variations, lead to significant stress variations in composites. Spurgeon [19] shows the variation in fibre volume fraction can be as high as ± 1%. Shaw [14] shows a 1.3% standard deviation for fibre volume fraction. Another important source of manufacturing related variation is ply thickness. According to Chamis [12], the coefficient of variation (CoV) can be as high as 5%.

Antonio and Hoffbauer [20] studied the uncertainty propagation on structural response of composites using three different approaches: a first-order local method, a Global Sensitivity Analysis supported by a variance-based method and an extension

* Corresponding author. Tel.: +61 (8) 92669204; fax: +61 (8) 92662681.
E-mail address: c.dong@curtin.edu.au (C. Dong).

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Nomenclature

A	extensional stiffness matrix for a laminate
B	coupling stiffness matrix for a laminate
D	bending stiffness matrix for a laminate
b	width of the specimen (mm)
D	maximum deflection (mm)
E_{11}	tensile modulus (GPa)
e_h	hybrid effect
G_{12}	shear modulus (GPa)
h	depth of the specimen (total thickness of the laminate) (mm)
h_c	thickness of the carbon/epoxy section (mm)
h_g	thickness of the glass/epoxy section (mm)
M	moments (N·m)
N	External forces (N)
P_{max}	the maximum load encountered before failure (N)
RI	Robust index
r_h	hybrid ratio
RS_F	robust flexural strength
RSS_F	robust specific flexural strength
S	span of the specimen (distance between to supporting pins) (mm)
S_C	compressive strength (MPa)
S_{Cc}	compressive strength of carbon/epoxy composites (MPa)
S_{Cg}	compressive strength of glass/epoxy composites (MPa)
S_{Cm}	modified compressive strength (MPa)
S_F	flexural strength of hybrid composites (MPa)
S_{Fc}	flexural strength of carbon/epoxy composites (MPa)
S_{Fg}	flexural strength of glass/epoxy composites (MPa)
S_{FRoM}	flexural strength from the rule of mixtures (MPa)
S_S	shear strength (MPa)
SS_F	specific flexural strength (kNm/kg)
V_{fc}	fibre volume fraction of the carbon/epoxy section
V_{fg}	fibre volume fraction of the glass/epoxy section
u, v, w	displacements (mm)
x, y, z	coordinates (mm)
$\boldsymbol{\varepsilon}$	strains
$\boldsymbol{\varepsilon}^{\mathbf{0}}$	membrane strains (strains of the mid-plane)
$\boldsymbol{\kappa}$	flexural strains (curvatures)
ρ_c	density of composites
ρ_{fc}	density of carbon fibres
ρ_{fg}	density of glass fibres
ρ_m	density of the matrix

Table 1
Typical properties of fibres and resin.

Material	Tensile modulus (GPa)	Tensile strength (MPa)	Density (kg/m^3)
Carbon fibres (T700S)	230	4900	1800
S-2 glass fibres	86.9	4890	2460
Epoxy	3.1	69.6	1090

of local variance to estimate the global variance over all domain of inputs. The uncertainty quantification and stochastic modelling approaches in FRP composites were reviewed by Sriramula and Chryssanthopoulos [21].

In this study, the robustness of unidirectional S-2 glass and T700S carbon fibre reinforced epoxy hybrid composites under flexural loading is investigated. The objective is developing an approach to the robust design of hybrid composites.

2. Flexural properties modelling

2.1. Material properties

The hybrid composites being investigated in this study are made by embedding two types of fibres, T700S carbon and S-2 glass, into one common matrix, epoxy. The typical material properties of the fibres and matrix are shown in Table 1. The lamina properties, including the longitudinal modulus E_{11}, the transverse moduli E_{22} and E_{33}, and the shear moduli G_{12}, G_{13} and G_{23}, are derived from the constituent properties using Hashin's model [22], and the lamina stiffness matrices are derived.

2.2. Flexural strength

With reference to our previous studies [2–8], the stacking configuration for the hybrid composites is achieved by partially substituting carbon/epoxy laminas on the compressive side of a full carbon/epoxy composite laminate for glass/epoxy laminas. A hybrid composite specimen under the three point bending is schematically shown in Fig. 1. The stress distribution can be conveniently obtained using the Classic Lamination Theory (CLT) [23]. The CLT is chosen for the computation efficiency because a large amount of computation is needed. The details can be found in our previous studies [6–8]. Only a brief description is given here for completeness.

For the purpose of quantitatively characterising the degree of hybridisation, hybrid ratio is introduced, which is the relative percentage of glass fibres with respect to all fibres, i.e.

$$r_h = \frac{h_g V_{fg}}{h_g V_{fg} + h_c V_{fc}} \tag{1}$$

According to the CLT, the strains in a laminate can be written in the form

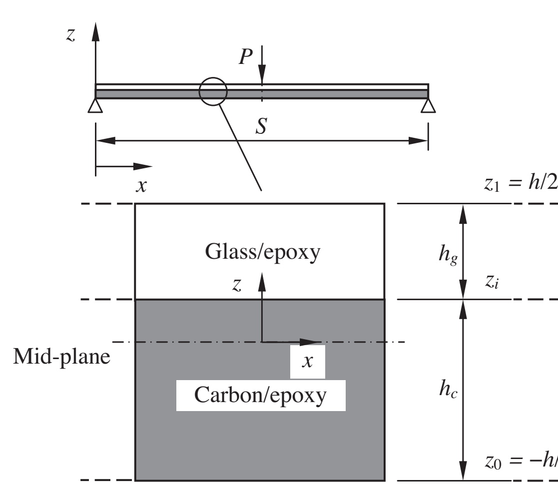

Fig. 1. A hybrid composite specimen under the three point bending.