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A study on the compressive strength of thick carbon fibre–epoxy laminates

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Abstract

This paper describes an experimental study that examines the effect of specimen size on the axial compressive strength of IM7/8552 carbon fibre/epoxy unidirectional laminates (UD). Laminate gauge length, width and thickness were increased by a scaling factor of 2 and 4 from the baseline specimen size of 10 mm × 10 mm × 2 mm. In all cases, strength decreased as specimen size increased, with a maximum reduction of 45%; no significant changes were observed for the axial modulus. Optical micrographs show that the failure mechanism is fibre microbuckling accompanied by matrix cracking and splitting. The location of failure in most specimens, and especially the thicker ones, is where the tabs terminate and the gauge section begins suggesting that the high local stresses developed due to geometric discontinuity contribute to premature failure and, hence, reduced compressive strength. Two generic quasi-isotropic multi-directional (MD) lay-ups were also tested in compression, one with blocked plies $[45_n/90_n/-45_n/0_n]_s$ and the other with distributed plies $[45/90/-45/0]_{ns}$ with $n = 2$, 4 and 8. The material used and test fixture was identical to that of the unidirectional specimens with three different gauge sections (30 mm × 30 mm, 60 mm × 60 mm and 120 mm × 120 mm) to establish any size effects. Strength results showed no evidence of a size effect when the specimens are scaled up using distributed plies and compared to the 2 mm thick specimens. All blocked specimens had similar compressive strengths to the sublaminate ones apart of the 8 mm specimens that showed a 30% reduction due to extensive matrix cracking introduced during the specimen's cutting process. The calculated unidirectional failure stress (of the 0° ply within the multidirectional laminate) of about 1710 MPa is slightly higher than the average measured value of 1570 MPa of the 2 mm thick baseline unidirectional specimen, suggesting that the reduced unidirectional strength observed for the thicker specimens is a testing artefact. It appears that the unidirectional compressive strength in thicker specimens (>2 mm) is found to be limited by the stress concentration developed at the end-tabs and manufacturing induced defects such as fibre misalignment, ply waviness and voids.

Keywords: A. Polymer matrix composites; B. Mechanical properties; B. Stress/strain curves; C. Buckling; C. Stress concentration; Size effects

1. Introduction

Considerable effort has been made over the years to understand the compressive behaviour and the mechanisms of compressive failure of thin (2–3 mm) unidirectional composite laminates. Numerous test methods and analytical models to predict the compressive strength have been developed. The models could be classified under two categories, i.e. microbuckling theories [1–3] and fibre kinking theories [4–6]. The test methods for thin specimens (2–3 mm) have been classified according to the way the load is applied, i.e. direct end-loading (ASTM 695, CRAG and Wyoming End-loaded method), shear loading (Celanese, IITRI) and mixed shear/direct end-loading (Aerospatiale Test fixture and Imperial College ICSTM method) [7].

Much less attention, however, has been paid to understand the compressive behaviour of thick unidirectional composite laminates even though requirement for advanced composite materials in thick structural sections (Airbus A380, Boeing 787) has significantly increased. This is caused by notorious difficulty of obtaining reliable test results. In fact, all problems related with compression testing become more serious and complicated with thicker

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composites, because of the tendency for premature failure due to global buckling or end crushing. In order to prevent the premature failure of the specimen, compression test specimens as well as test fixtures should be manufactured to provide a uniform one-dimensional compressive stress field, carefully considering the following factors: properties of the tabbing materials, tab bond characteristics, tab thickness and reliable specimen production procedures. Nevertheless, many workers often and mistakenly dismiss these factors as being of no importance. Of course, in addition to these parameters, specimen geometry, test fixture design and specimen misalignment in the fixture, can contribute to premature failures and reduced compressive strength values. Recent studies, Componeschi [8], Hsiao [9], Daniel [10] and Lee [11] made an effort to develop a suitable compression test method for thick composites and investigated the effect of specimen thickness on the compressive strength. It was found that the failure strength decreases with increasing thickness of the unidirectional laminate, but most of the failures occurred near or at the specimen end where the load is introduced (end crushing). It appears that existing test methods have not provided accurate and reproducible compressive properties for the analysis and design of thick sections/structures. The need remains to develop a reliable compression test method for such thick constructions.

In terms of scaling of unidirectional laminates, the tendency of the thickness effects was revealed in the literature even though the thick specimens failed prematurely [8–12]. However, limited studies have been performed on 3D scaling effects on the compressive strength, where all three dimensions are scaled up accordingly. In trying to explain the unexpected low failure strength of thick composites, possible explanations could fall into the categories of material or manufacturing related issues [8] and several questions can be raised. In terms of material aspects, the elastic constants or strength determined for thin laminates may not be applicable to thick composites. What are the trends for the compressive properties of composite materials with increasing thickness? In terms of manufacturing, does thickness change have an influence on fibre volume fraction, void content, ply or fibre waviness? If manufacturing quality were affected directly by the thickness change of the composite, a thickness effect would be expected since the compressive strength is governed by and is sensitive to these defects.

In the present study, a carefully thought procedure for the design of a thick compressive test specimens is presented. The cause of the premature failure of 2–8 mm thick specimens made from the IM7/8552 carbon fibre/epoxy system is identified from experimental observations and numerical stress analysis. Stress concentration effects at the junction of the end-tab and gauge section using plain and waisted specimens are investigated. The 3D scaling effects on the compressive strength of IM7/8552 unidirectional laminates are systematically examined. In addition, two generic quasi-isotropic lay-ups are also tested in compression, one with blocked plies $[45_n/90_n/-45_n/0_n]_s$ and the other with distributed plies $[45/90/-45/0]_{ns}$ with $n = 2$, 4 and 8. The calculated failure stress of the 0° ply in the multidirectional laminates is compared to that measured value for the 0° unidirectional laminate.

2. Experimental procedure

2.1. Material and lay-up

The specimens were fabricated from commercially available (Hexcel Composites Ltd.) carbon/epoxy pre-impregnated tapes 0.125 mm thick. The tapes were made of continuous intermediate modulus IM7 carbon fibres pre-impregnated with Hexcel 8552 epoxy resin (34 vol% resin content). The material was laid up by hand in 0.25 m × 0.3 m unidirectional plates $[0_4]_{ns}$ with $n = 2$, 3, 4, and 8 (i.e. 2, 3, 4 and 8 mm thick). In addition, two quasi-isotropic lay-ups were fabricated, one with blocked plies $[45_n/90_n/-45_n/0_n]_s$ and the other with distributed plies $[45/90/-45/0]_{ns}$ with $n = 2$, 4 and 8 in order to gain an insight into the efficiency of 0° plies when employed in multidirectional laminates under uniaxial compression. The standard cure cycle recommended by Hexcel Composites Ltd. was used for the thin laminates (<4 mm thick). The thicker laminates had to dwell in the autoclave for a longer period of time to allow even heat distribution throughout the panel and diminish the possibility of an exothermic reaction (heat energy that causes uncontrollable temperature rise within thick laminates). The in-plane stiffness and strength properties of the IM7/8552 unidirectional laminates provided by the materials manufacturer are presented in Table 1; values for the T800/924C carbon/epoxy system are provided for comparison purposes.

2.2. Specimen geometry

In order to develop a satisfactory procedure for the design of a compressive test specimen certain constraints

Table 1
Elastic properties of the IM7/8552 and T800/924C systems

Property	E_{11} (GPa)	E_{22} (GPa)	G_{12} (GPa)	v_{12}	σ_{11C} (MPa)	σ_{22C} (MPa)	$\tau_{12\#}$ (MPa)
IM7/8552	150	11.0	4.6	0.30	1690	250	120
T800/924C	161	9.25	6.0	0.35	1615	250	105

(σ_{11C} = longitudinal compressive strength and σ_{22C} = transverse compressive strength, $\tau_{12\#}$ = in-plane shear strength)