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Design of end plugs and specimen reinforcement for testing ±55° glass/epoxy composite tubes under biaxial compression

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Abstract

Finite element stress analysis predictions used in the development of a test specimen and grips for testing composite tubes under biaxial compression are reported. Specimen end reinforcement and end closures of different shapes (including cylindrical, conical and radiused plugs) were analyzed and a shape that gives minimal stress concentration was established. An axisymmetric model and linear elastic orthotropic material properties were employed in the finite element analysis and several different combinations of compressive loading were analysed. Experimental results are presented for two; ±55° filament wound glass/epoxy (GRP), strain-gauged cylinders, one with end reinforcement and the other without. Both specimens were tested to destruction under external pressure loading that produced biaxial compression with circumferential:axial stresses in the ratio SR = −2/−1. A good correlation was observed between the finite element analysis and experimental strain distributions in both cylinders and the optimised shape of end plug and end reinforcement gave low strain concentrations.

Keywords: End closure; Biaxial compression; Composite tubes; External pressure; Finite element analysis

1. Introduction

One of the important requirements in the design of an effective test specimen for mechanical characterisation of material behaviour under multiaxial loads is the need to ensure that uniform stresses are obtained in the test section and that failure takes place within the gauge length and not somewhere else. Cylindrical tubes have gained widespread recognition as good specimens for testing fibre reinforced composite materials under uniaxial and biaxial loads, Refs. [1–12]. Thin walled tubes, typically of radius to thickness ratio R/h of 40, are commonly used for obtaining biaxial tension failure strengths where the stresses are generated by the application of combined internal pressure (circumferential tension) and axial tension, see for instance Ref. [1]. A number of theoretical investigations were performed with the aim of ensuring that characterisation of biaxial tension strength is affected as little as possible by boundary conditions. Analytical solutions, based on thin shell theory and beams on elastic foundations, were used, Ref. [2], to design methods for gripping and reinforcing the ends of anisotropic tubes tested under

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Nomenclature

b	length of tapered portion of end reinforcement
D_i	tube internal diameter
E	Young's modulus
G	shear modulus
h	tube wall thickness
H	thickness of reinforcement
P_0	external pressure
R	tube internal radius
R_t	meridional radius of curved taper
R_p	meridional radius of end plug
SR	ratio of hoop:axial stresses
ε	strain
υ	Poisson's ratio
σ	stress

Subscripts

θ	hoop direction
r	radial or through-thickness direction
x	axial direction

combined axial load and internal pressure. It was important to locally thicken the ends of tubular specimens because discontinuity in loading, e.g. at seals, produces local shell bending which may cause premature failures, Ref. [2]. Numerical methods, employing finite element analyses, were also successfully used to study the stress and strain distributions in thin quasi-isotropic and angle ply tubes under combined internal pressure and axial load, Refs. [3–7,20]. Lee et al., Refs. [3,4] have also reported experimental results showing good correlation with the numerical results of tubes with axisymmetric steps. By and large, a fair amount of test data and theoretical analyses have been generated to describe the behaviour of composite tubes under biaxial tension loading.

In contrast, little previous work is available on testing cylinders under combined external pressure and axial compression to obtain the biaxial compressive (crushing) failure strength. Buckling rather than crushing was observed to take place in thin composite tubes under external pressure, Refs. [8,9,19], and structural instability or premature failure seemed to govern the behaviour in the previously published results. Therefore, the quoted failure stresses are actually affected by the geometry of the specimens. To achieve crushing, the wall thickness of the tubes should be increased so that buckling is avoided, Refs. [10–12]. End failure and stress concentration near end closures remained potential sources for premature failure.

Designing an efficient test specimen with suitable end closures for external radial pressure biaxial compressive crushing tests, has received some attention and recent work in this area is reported in Refs. [11,13,14]. Miller [13] used thin shell theory to propose a method for reducing the interlaminar shear stress and bending stresses in thin 0°/90° cross plied glass/epoxy tubes under external radial pressure. That was achieved by studying two shapes of contoured end plug that will prevent large end discontinuity moments and shear stresses. Blake and Starbuck [14] also applied thin shell theory, based on the Donnell approximations, to obtain the best shape of contoured end plugs which reduce end effects in composite cylinders under external radial pressure. Transverse shear and axial bending deformations were taken into consideration. Graham [11] used a finite element analysis (ASAS-NL) to study the effect of reinforcement shape on the stress distribution in carbon/epoxy tubes under a single circumferential to axial stress ratio involving external pressure loading. No details are available on the end closures used.

The present study was undertaken as a part of an extensive programme of work to establish design data for ±55° E-glass/epoxy laminates under a wide range of biaxial compression-compression stresses, Refs. [17,18]. In the present work, the ABAQUS finite element package [15] was used to perform axisymmetric stress analysis to obtain acceptable test specimen and end closure geometries for testing thick walled composite tubes under combined external radial pressure and axial compression. Various plug shapes were investigated and a shape was chosen that gives minimal stress concentration. Also, the effect of end reinforcement on the stress distribution in the test piece was studied. Experimental results are also presented showing the strain distribution along two tubular specimens; one with end reinforcement and another without, both subjected to external hydrostatic pressure.

2. Finite element analysis

2.1. Details of the structure

The structure analyzed is basically a ±55° angle ply filament wound E-glass/epoxy (GRP) tube subjected to combined external pressure and axial compression. (The angle is measured between fibre direction and axial direction of the tube). For most parts of the analysis, the loading was by "external hydrostatic pressure" that gives a stress ratio of circumferential (hoop) stress to