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Fatigue strength of tubular carbon fibre composites under bending/torsion loading

C. Capela [a,b,*], J.A.M. Ferreira [a,c], T. Febra [b], J.D. Costa [a,c]

[a] CEMUC, Universidade de Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal
[b] Department of Mechanical Engineering, ESTG, Polytechnic Institute of Leiria, Morro do Lena – Alto Vieiro, 2400-901 Leiria, Portugal
[c] Department of Mechanical Engineering, Universidade de Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

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ABSTRACT

Carbon fibre reinforced polymer composites have been increasingly used on structures frequently subjected to biaxial fatigue loadings. This paper studies the fatigue behaviour of tubular carbon fibre composites under in phase biaxial bending/torsion dynamic loadings. Particularly, it was analysed both the torsion stress and mean stress effects on the fatigue strength and failure mechanisms. Fatigue strength decreases significantly with increased torsional/bending stresses ratio, while the damage becomes faster. For the cases in which a torsion loading was applied the effect of the mean stress on the fatigue strength seems to be well fitted by using a quadratic equation.

1. Introduction

Carbon fiber reinforced polymer (CFRPs) composite materials allow a significant reduction in weight and are widely used in structures and components of motor vehicles, airplanes, high-speed trains, associated with the consequential fuel saving. In many cases, these structural components are subjected to complex fatigue load histories characterized by changes in the amplitude, stress ratio (R), frequency and waveform of the cyclic stresses and combined bending and torsion biaxial loading.

Literature reports abundant studies about failure of composite materials subjected to biaxial loadings, namely for carbon/epoxy tubular specimens produced by filament wound [1,2], quasi-isotropic hand layed up [3] and lapped moulding technique [4]. Amijima et al. [5] studied the biaxial failure on plain-weave glass/epoxy laminates fabricated by the wet-winding technique. Dominant failure mechanisms have been identified like: fibre breakage, pull-out, and matrix cleavage and hackle formation resulting from interfacial tensile or shear failure [6]. For graphite/epoxy thin-walled tubes with $[0/90]_s$ and $[\pm 45]_s$ woven filaments it was observed that matrix shear cracking or matrix tension cracking mode were always the failure mechanisms observed in the first ply [7].

Ferry et al. [8] studied the fatigue damage of both bending and torsion loading on unidirectional glass-fibre/epoxy composite bars, observing that damage processes occurred through the fibre failure, delamination and matrix cracking. These authors concluded that damaging occurred by several complex processes, depending on both the ratio between bending and torsion stresses and the ratio between minimum and maximum stresses. One method widely used for model the fatigue damage is quantifying the variation in stiffness, usually in terms of the modulus of elasticity, against the number of fatigue cycles. In many cases it was observed that in the first cycles the stiffness decays significantly followed by a second long period with a very low decrease. During this stage starts both the rupture of the fibres and polymer matrix micro-cracking. Afterwards, delamination between laminate layers and its separation occurs, causing a rapid rupture and consequently a sharp decay of stiffness [9].

El-Assal and Khashaba [10] studied the fatigue behaviour of unidirectional glass fibre reinforced polyester (GFRP) composites under in-phase combined torsion/bending loading concluding that torsional fatigue strength was significantly lower than pure bending fatigue strength and that the endurance limit of combined torsion/bending fatigue strength was approximately half the fatigue limit of pure bending fatigue strength. Fawaz and Ellyin [11,12] proposed a multiaxial model for life prediction, based on

* Corresponding author at: Department of Mechanical Engineering, ESTG, Polytechnic Institute of Leiria, Morro do Lena – Alto Vieiro, 2400-901 Leiria, Portugal. Tel.: +351 244820300; fax: +351 244820310.

E-mail address: ccapela@estg.ipleiria.pt (C. Capela).

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the modification of a reference fatigue curve to account for the actual load ratio and multiaxial loading condition. Quaresimin et al. [13] re-analysed some of the multiaxial fatigue data available in the literature to verify the accuracy of life prediction by Fawaz–Ellyin method and by a polynomial function criterion. Recently, Quaresimin and Carraro [14] studied the biaxial fatigue behaviour of unidirectional composites using tubes made of glass/epoxy plies, with the fibres oriented at 90° with respect to the tube's axis and tested under combined tension–torsion loading, concluding that the damage evolution during fatigue testing did not show a measurable and stable growth. The transverse crack propagates unstably all along the tube circumference leading to a complete separation of the sample in very few cycles. Due to this behaviour, axial and torsional stiffness exhibited only a sudden drop in correspondence of the final failure. The same authors [15] report an extended study using tubular specimens with three different lay-up ($[90_n]$, $[0_F/90_{U,3}]$ and $[0_F/90_{U,3}/0_F]$) tested under combined tension/torsion loadings showing that the presence of shear stress significantly reduces the life spent for initiation of the transverse crack, for a given value of the transverse stress and the crack nucleation resistance of the $[0_F/90_{U,3}/0_F]$ tubes is slightly higher than that of the $[90_{U,4}]$ ones. Quaresimin et al. [16] compare the evolution of fatigue damage in laminates with that measured on tubes tested under tension–torsion loading conditions. Using a designed lay-up of the laminates able to introduce a local multiaxial stress state comparable to that present in the tubes subjected to external multiaxial loading these authors showed that the evolution of fatigue damage in multidirectional laminates tested under uniaxial cyclic loading and tubes tested under external multi-axial (tension–torsion) loading was basically the same. Schmidt et al. [17] analysed the damage development in glass fibre winding specimens during biaxial fatigue loading using non-destructive testing methods which reveals that initiation of final failure in the specimens is caused by local fibre waviness.

The fatigue behaviour of composites is highly dependent on the stress ratio, R, as reported in several literature studies [18–21]. El-Kadi and Ellyin [19] observed that for a given maximum stress in tension–tension loading the fatigue life increases with the increasing of stress ratio. In compression–compression loading the increase of R reduces the fatigue life of the composites. Rosenfeld and Huang [20] studied the effect of the compressive loading on the fatigue behaviour of graphite/epoxy laminates for $R = 0$, $-\infty$ and -1. They concluded that a significant life reduction occurs for both $R = -\infty$ and $R = -1$, being higher for $R = 0$. Petermann and Schulte [21], related the highly dependency on R with creep effect for ±45° angle-ply laminates of carbon-epoxy tested in tension–tension fatigue.

The influence of the mean stress on the fatigue life of a material is usually analysed in an envelop, known as the "stress amplitude–mean stress diagram", where the stress amplitude (σ_a) is a function of the mean stress (σ_m) for a given fatigue life. Abd Allah et al. [22] used this analysis method to shows that the estimated values of σ_a using the Peterson's equation [23] have the best agreement with the experimental data. Also, Boller [24] and Crowther et al. [25] concluded that for 0° and ±15° laminates and sandwich composites, respectively, the Goodman equation did not fit well the effect of the mean stress. Mallick and Zhou [26], for short E-glass fibre reinforced polyamide 6.6, and Reis et al. [27], for balanced woven bidirectional carbon/epoxy laminate composites, concluded that the effect of the mean stress on the fatigue strength can be described by a modified quadratic equation.

The objective of present work was to obtain experimentally fatigue design curves on tubular carbon fibre composites under bending, torsion and bending/torsion loadings for different stress ratio (R) and to analyse the effectiveness of the actual models for the prediction of the fatigue life and the effect of the mean stress on this particular complex stake laminate system.

2. Materials and procedure

The aim of the present work is to study the fatigue behaviour of tubular specimens manufactured in epoxy matrix resin reinforced by woven balanced biaxial carbon fibres. Thin-walled tubular specimens with one of the fibres aligned at 90° and other crossed at 0° with respect to the tube axis were manufactured and tested. The epoxy resin used was SR 1500, formulated by bisphenol A and F and it was combined with the hardener SD 2503, both supplied by Sicomin, Marseille, France. This epoxy system has good waterproof and adhesion properties and is commonly used in ship building and aerospace industry. Carbon woven fabric ref. 195 (196 g/m^2) was produced by Rebelco, Portugal, using and carbon fibre HS 3 K, supplied by Toray, Japan.

Tubular specimens were manufactured with 4 carbon layers using a rigid polyurethane mould and a moulding pressure element, as schematically shown in Fig. 1. The cure process was 8 h in vacuum bag at 20 °C. The post-curing cycle was as follows: 24 h at 20 °C followed by 24 h at 40 °C. The geometry and dimensions of the specimens are shown in Fig. 2(a). This manufacturing

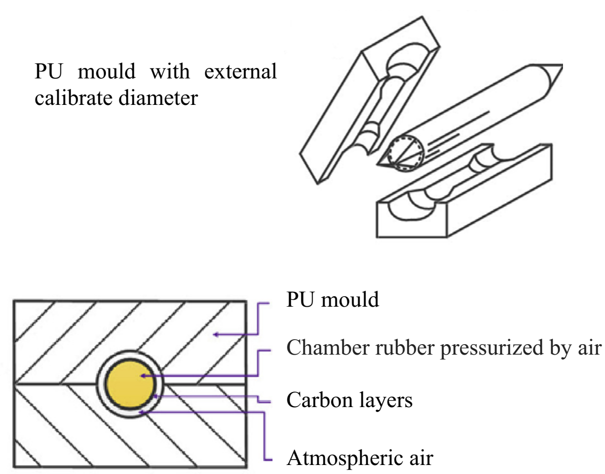

Fig. 1. Schematic view of the moulding process.

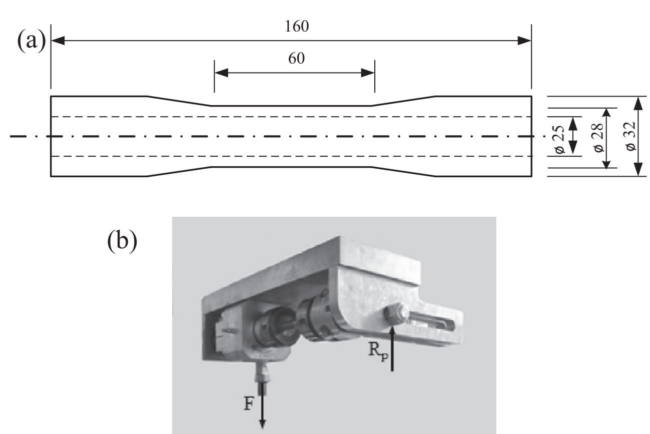

Fig. 2. Specimens geometry and fatigue testing device. (a) Tubular specimen. (b) Bending/torsion testing device.