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Influence of load ratio on the biaxial fatigue behaviour and damage evolution in glass/epoxy tubes under tension–torsion loading

M. Quaresimin *, P.A. Carraro, L. Maragoni

Department of Management and Engineering, University of Padova, Stradella S. Nicola 3, 36100 Vicenza, Italy

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ABSTRACT

An extensive experimental campaign was carried out to understand the influence of the multiaxial stress state and load ratio on the matrix-dominated damage initiation and evolution in composite laminates under fatigue. Tubular glass/epoxy specimens were tested under combined tension–torsion loadings with different values of the load ratio and biaxiality ratio (shear to transverse stress ratio). Results are reported in terms of S–N curves for the first crack initiation and Paris-like diagrams for crack propagation, showing a strong influence of both parameters. Fracture surfaces were also analysed to identify the damage mechanisms at the microscopic scale responsible for the initiation and propagation of transverse cracks. Eventually, a crack initiation criterion presented by the authors in a previous work is applied to the experimental data showing a good agreement.

1. Introduction

Because of the fast-growing structural usage of composite materials in several fields, such as aerospace, automotive, shipbuilding and wind turbines, increasing the knowledge on the multiaxial fatigue behaviour of this class of materials is becoming a matter of primary concern.

Research in this direction is driven also by the absence of reliable predictive models and design criteria of general validity, capable of accounting for all the parameters influencing the complex fatigue behaviour of composites [1], which depends on the laminate stacking sequence, geometry and loading conditions.

In general, the fatigue life of a multidirectional laminate is characterised by a progressive damage evolution, mostly occurring in the form of nucleation and propagation of off-axis matrix cracks [2–6] which cause a global stiffness degradation much before the final failure (see Refs. [7–11] amongst the others). Accordingly, as a first step to provide tools for the prediction of crack initiation and propagation in the off-axis layers of a laminate, it is necessary to investigate and understand the matrix-dominated fatigue behaviour of unidirectional (UD) plies.

More than one thousand data from the literature were collected in Ref. [1] with the aim to obtain information on the influence of the main design parameters on the fatigue behaviour of composite laminates under multiaxial loadings. From this investigation it was concluded that the presence of shear stress (i.e. the multiaxial stress state) and the load ratio $R = \sigma_{min}/\sigma_{max}$ are the most important parameters, and their effects have not been clarified enough. Indeed, with particular reference to the matrix-dominated behaviour, no clear data on the behaviour of UD laminates are available, most of the literature being focused on laminates with particular stacking sequences [1].

The degree of multiaxiality of a specific loading condition can be effectively quantified by the biaxiality ratios, defined as follows [1,12]:

$$\lambda_1 = \frac{\sigma_2}{\sigma_1}, \quad \lambda_2 = \frac{\sigma_6}{\sigma_1}, \quad \lambda_{12} = \frac{\sigma_6}{\sigma_2} \tag{1}$$

where σ_1, σ_2, and σ_6 are the longitudinal, transverse and in-plane shear stresses, respectively, as evaluated in the material coordinates system. In particular, parameter λ_{12} is of great interest when dealing with the matrix-dominated fatigue behaviour [12].

With the aim to fill the lack of comprehensive experimental investigations and results of general validity, the authors recently developed a testing procedure suitable to characterise the matrix-dominated fatigue response of unidirectional plies [12,13]. Glass/epoxy tubes with the fibres aligned at 90° with respect to the tube's axis and subjected to combined tension/torsion loadings were found to be the best solution to achieve a stress state characterised by the presence of σ_2 and σ_6 only. This configuration allows the λ_{12} ratio to be modulated from 0 (pure tension) to infinity (pure torsion), resulting in a very attractive way for characterising the multiaxial fatigue behaviour in terms of crack

* Corresponding author. Tel.: +39 0444998723.
E-mail address: marino.quaresim@unipd.it (M. Quaresimin).

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initiation. Later, the authors slightly modified the specimen lay-up introducing thin internal and external fabric layers to induce a stable and observable propagation under mixed I + II mode conditions (due to tension and torsion loadings, respectively) [14]. Tubes were tested with four values of the biaxiality ratio λ_{12} (0, 0.5, 1, 2) and load ratio $R = 0.05$. A strong influence of the biaxiality ratio was found on the cycles spent for crack initiation, the crack growth rate and the damage mechanisms at the microscopic scale. Experimental evidences of damage initiation and evolution were also considered as a support in the development of a crack initiation criterion for UD composites under multiaxial loadings [15].

As already mentioned, another important parameter for the fatigue behaviour of composites is the load ratio R. In Ref. [16] filament wound glass/epoxy tubular specimens with lay-up [±θ] (with $\theta = 35°$, 55° and 70°) were tested with load ratio equal to 0 and −1 showing a strong influence of the load ratio on the S–N curves. In particular, a pronounced detrimental effect was seen for $\theta = 35°$ and $R = -1$, with respect to the fatigue curve for $R = 0$. A lower, but still evident effect of the load ratio was found also for $\theta = 55°$ and 70°. However, as the data were related to the final failure of the tubes, these results are not useful to describe and understand the initiation and evolution of damage at the ply level.

According to the authors' best knowledge this is the only experimental investigation on the effect of the load ratio on tubes under combined tension–torsion loadings. However, recently we proved that the crack initiation and propagation are essentially the same for either *external* multiaxiality (due to external loads in multiple directions) or *internal* multiaxiality (due to material anisotropy, even in the presence of uniaxial loads), provided that the local stress state is the same, at least for positive load ratios (see Ref. [6]). Nevertheless, if buckling is avoided when compressive loads are applied, some useful information on the multiaxial fatigue behaviour of UD plies can be extracted from flat coupons tested under a uniaxial load. In this view, also data from the literature on flat laminates, characterised by an *internal* multiaxiality, can be considered for the analysis of the influence of the load ratio.

Useful data are presented in the works by El-Kadi and Ellyin [17] and Kawai and Suda [18], who also proposed phenomenological approaches to account for the influence of the load ratio [17,19]. Tests were carried out on UD glass/epoxy [17] and carbon/epoxy [18] laminates, subjected to a cyclic uniaxial load with different off-axis angles θ. In Ref. [17] three values of the load ratio were considered ($R = -1$, 0 and 0.5) and five different off axis angles, namely $\theta = 0°$, 19°, 45°, 71° and 90°. Focusing on the matrix-dominated behaviour ($\theta > 0$), strong differences between the S–N curves for $R = 0$ and 0.5 were observed for each value of θ, the slope being lower for higher values of R. Similar conclusions can be drawn for $R = 0$ and −1 and $\theta = 19°$, whilst negligible differences were found between the curves for R = 0 and −1 related to off-axis angles $\theta = 45°$, 71° and 90°. In Ref. [18] tests were carried out with $R = -1$, 0.1 and 0.5 and $\theta = 0°$, 15°, 30°, 45° and 90°. In this case a clear influence of R was reported even for high off-axis angles, in particular on the slope of the S–N curves which were steeper as R decreased. Contradictory conclusions can be drawn from Refs. [17,18] concerning the effect of the load ratio. Indeed, according to Ref. [17], the presence of a compressive part of the cycle does not seem to influence the life to crack initiation when the shear stress is very low. This conclusion, however, is not supported by the data reported in Ref. [18].

The available results on the influence of R on the matrix-dominated fatigue behaviour of generic laminates do not allow therefore general conclusions to be drawn with reference to the synergistic effect of the load ratio and the multiaxial stress state.

Within this context, the present work aims at investigating the combined effect of the load ratio and the external multiaxial loading on the fatigue damage evolution. In particular the fatigue crack initiation and propagation and the damage mechanisms at the microscopic scale, leading to the initiation and propagation of a transverse crack, were investigated. Tubular samples were tested with $\lambda_{12} = 0$, 1, 2 and $R = -1$, 0.5, and results are compared with those obtained in Ref. [14] for $R = 0.05$. The influence of both parameters on crack initiation and propagation, as well as on the damage mechanisms at the microscopic scale, are discussed in details. Eventually, the criterion for crack initiation under multiaxial fatigue loadings recently proposed by the authors [15] is applied to the new results, showing a good agreement.

2. Materials, geometry and test equipment

The same tubular specimens tested in Ref. [14] with stacking sequence $[0_F/90_{UD,3}/0_F]$ were adopted, where the subscript F means fabric whereas UD stands for unidirectional. Tubular samples have the important intrinsic advantage of preventing macroscopic buckling under compression loadings. For the sake of completeness the geometry of the tubes is shown in Fig. 1. The tubes were produced by mandrel wrapping and successively cured in autoclave (1 h at 6 bars and 140 °C). The internal diameter of the tubes was 19 mm, and from the initial 1 m long tubes, 150 mm long specimens were cut. Glass/epoxy pre-preg tabs were bonded to the ends of the tubes to reach a calibrated length of 70 mm, and then cured at 80 °C for 8 h. The external diameter of the tabbed portion of the specimens was 24 mm. To avoid cracking of the specimen at the ends of the tabs, a fillet was made with a two-part epoxy structural adhesive (9323 B/A by 3 M), cured at 40 °C for 4 h. The following materials were used to manufacture the specimens:

– UE 400 REM by SEAL-Italy: glass/epoxy UD pre-preg, thickness = 0.38 mm, used for the 90° layers;
– EE 106-ET443 by SEAL-Italy: glass/epoxy fabric pre-preg, thickness = 0.13 mm, used for the internal and external fabric layers.

The elastic and strength properties of these materials, listed in Table 1, were obtained by testing 0°, 45° and 90° flat specimens under static tensile loads, as reported in Refs. [12,14].

Both fatigue and quasi-static tests were carried out on the tubular specimens under combined tension/torsion loadings. This induces a stress state in the 90° plies characterised mainly by the presence of the transverse stress σ_2 and in-plane shear stress σ_6. The magnitude of the stress parallel to the fibre direction due to the presence of the thin fabric layers is, in fact, very low ($<0.1\sigma_2$) and assumed to have a negligible influence when compared to the longitudinal strength of the ply [14]. Experiments were conducted by means of a MTS 809 axial/torsional machine equipped with a 10 kN/110 Nm load cell. Quasi-static tests were first carried out under load control in pure tension, pure compression, combined tension and torsion with $\lambda_{12} = 1$, 2, and combined compression and torsion with $\lambda_{12} = 1$, 2. Axial and torsional loads were proportionally applied. The damage onset and evolution were monitored by a FLIR SC7600 MW infrared camera (temperature accuracy 20 mK) and two aluminium reflectors were positioned on the back of the specimen, providing a 360° view to the infrared camera. Quasi-static tests were carried out at a loading rate equal to 0.3 MPa/s, low enough to allow the observation of the damage initiation to be done by means of thermographic analyses. Fatigue tests were carried out under load control, frequency $f = 10$ Hz, load ratio $R = \sigma_{2,min}/\sigma_{2,max} = \sigma_{6,min}/\sigma_{6,max} = -1$, 0.5 and biaxiality ratios $\lambda_{12} = \sigma_6/\sigma_2 = 0$, 1, 2 (experimental data for R = 0.05 and the same values of λ_{12} were already reported in Ref. [14]). Proportional in phase axial and torsional loads were applied and the damage onset and evolution (nucleation and propagation of transverse cracks in the 90° layers) were monitored. To this end the lock-in thermographic technique was used, together with eye-observations