INFLUENCE OF THE STRESS RATIO ON THE MULTIAXIAL FATIGUE BEHAVIOUR OF GLASS/EPOXY TUBES

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

Department of Management and Engineering, University of Padova, Stradella S. Nicola 3, Vicenza, Italy
** marino.quaresimin@unipd.it*

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Abstract

In the present work the influence of the multiaxiality condition and of the stress ratio on the fatigue behavior of glass/epoxy tubes is investigated. Fatigue tests have been conducted on tubular specimens subjected to combined tension-torsion loading resulting in a biaxial stress state with the presence of transverse and in-plane shear stresses. Three values of the stress ratios have been also investigated (-1, 0 and 0.5). Fatigue curves, relating the maximum cyclic transverse stress to the cycles spent for the initiation of the first crack, have been found to be strongly dependent on the multiaxiality condition and on the stress ratio.

1 Introduction

Because of the fast-growing structural usage of composite materials in many fields (aerospace, automotive, shipbuilding, wind turbines…), modeling the multiaxial fatigue behavior of this class of materials is becoming a matter of primary importance. Research in this direction is driven also by the fact that, at present, there are not predicting models and design criteria that are completely reliable and of general validity, as extensively discussed in [1]. In addition, an extensive and clear experimental investigation is still missing, as well as the deep knowledge of the damage mechanisms bringing a laminate to fatigue failure in multiaxial conditions [1].

Being the fatigue life of a multidirectional laminate characterized by a progressive damage, mostly occurring in the form of nucleation and propagation of off-axis matrix cracks [2], it is necessary to investigate and understand, first, the non-fiber-dominated fatigue behavior of the single lamina, under multiaxial loading.

As shown in [1], the multiaxiality condition and the stress ratio R are important parameters influencing the fatigue behavior of composite materials.

The multiaxiality condition can be quantitatively described by means of *biaxiality ratios,* defined as follows [1]:

$$\lambda_1 = \frac{\sigma_2}{\sigma_1},\ \lambda_2 = \frac{\sigma_6}{\sigma_1},\ \lambda_{12} = \frac{\sigma_6}{\sigma_2} \qquad (1)$$

in which σ_1, σ_2, e σ_6 are, respectively, the longitudinal, transverse and in-plane shear stresses, expressed in the material coordinates system. In particular, the parameter λ_{12} is of fundamental interest concerning the matrix-dominated fatigue behavior. In a recent work by

Carraro and Quaresimin [3] an extensive experimental analysis was conducted in order to understand the effect of λ_{12} on the nucleation and propagation of cracks under fatigue loading. Tubular glass/epoxy specimens subjected to combined tension/torsion cyclic loading with R = 0 were tested, showing a strong influence of this parameter even on the damage mechanisms at a microscopic level.
The aim of the present work is to investigate the influence of the stress ratio R on the matrix cracks nucleation under multiaxial loading.
In a previous work by Qi and Cheng [4] tubular specimens with lay-up [±θ] (with θ = 35°, 55° and 70°) were tested with stress ratio equal to 0 and -1, resulting in a strong influence of R on the fatigue S-N curves plotted in terms of the maximum cyclic applied stress. In particular, a dramatic detrimental effect has been found for θ = 35° and R = -1, with respect to the fatigue curve for R = 0. A lower, but still evident effect was also found for θ = 55° and 70°. However, since the reported fatigue curves were related to the final failure of the tubes, these results are not useful to understand the behavior of a single lamina.
In this direction, more useful data can be found in the works by El Kadi and Ellyin [5] and by Kawai and Suda [6], where tests were conducted on unidirectional glass/epoxy and carbon/epoxy laminae respectively, subjected to cyclic uniaxial load with different off-axis angles θ. In [5] three values of the stress ratio were considered (R = -1, 0 and 0.5) for off axis angles θ = 0°, 19°, 45°, 71° and 90°. Strong differences between the fatigue curves, expressed in terms of the maximum cyclic global stress, for R = 0 and 0.5 were observed for each value of θ, the slope being lower for higher value of R. Similar conclusions can be drawn for R = 0 and -1 and θ = 0° and 19°, while very small differences were found between the curves for R = 0 and -1 related to off-axis angles of 45, 71 and 90 degrees.
In [6] tests were conducted for R = -1, 0.1 and 0.5 and θ = 0°, 15°, 30°, 45° and 90°. In this case a clear influence of R was always found, in particular on the slope of the S-N curves, becoming steeper as R decreased.
The present work has the objective to investigate the effect of R and its possible dependence on the multiaxiality condition. Fatigue tests are carried out on $[0_F/90_{UD,3}/0_F]$ tubes (the subscripts F and UD denote fabric and unidirectional lamina respectively) for λ_{12} = 0, 1, 2 and R = -1, 0, 0.5, focusing the attention on the nucleation of cracks in the 90° layers.

2 Materials and test equipment

Tubular specimens have been produced by *mandrel wrapping* and cured in autoclave by means of a curing cycle characterized by the permanence for one hour at the pressure of 6 bars and temperature of 140°C.
The following materials have been used:

- UE 400 REM, produced by SEAL: glass/epoxy UD pre-preg, thickness = 0.38 mm, for the 90° layers
- EE 106-ET443, produced by SEAL: glass/epoxy fabric pre-preg, thickness = 0.13 mm, for the internal and external 0° fabric layers.

The in plane elastic and static strength properties of these materials are listed in table 1.
Nominal internal and external diameters of the tubes are of 19 mm and 21.8 mm respectively. 1 meter long tubes were obtained after the curing process, and from them, 150 mm long specimens have been cut. At the ends of the specimens, glass/epoxy fabric tabs have been applied and cured in a woven at 80°C for 8 hours, reaching a final gauge length of 70 mm and a diameter of the tabbed portion equal to 24 mm. In order to avoid the failure under the tabs, which represent a critical point because of the induced stress concentrations, a fillet has been applied by means of a two parts epoxy adhesive, cured at room temperature, as shown in figure 1.

	$\sigma_{1,UTS}$ (MPa)	$\sigma_{2,UTS}$ (MPa)	$\sigma_{6,UTS}$ (MPa)	E_1 (MPa)	E_2 (MPa)	G_{12} (MPa)	ν_{12}
UD400 - REM	973 ±60	50 ±7	98	34860 ±2360	9419 ±692	3193	0.326 ±0.015
EE106 – ET443	257 ±7	239 ±3	80	17033 ±490	16359 ±205	3032	0.159 ±0.005

Table 1: Properties of the adopted materials

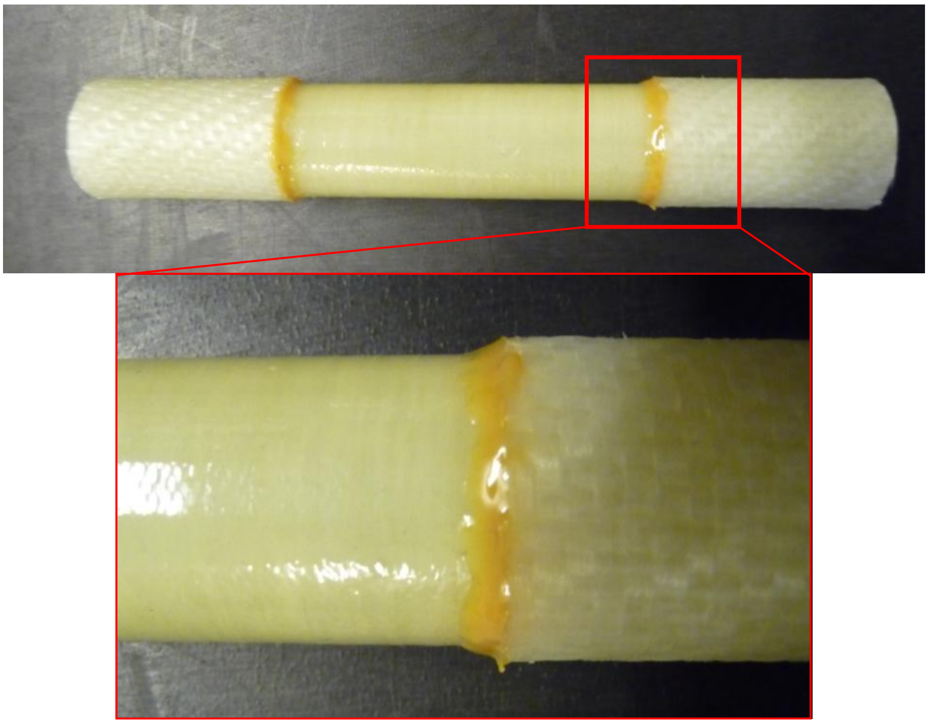

Figure 1: geometry of the specimens with end tabs and fillet

Fatigue tests were conducted by means of MTS 809 axial/torsional machine, in load control, with frequency of 8 Hz, and R = -1, 0, 0.5. Combined tension and torsion loadings have been applied in order to achieve the required biaxial stress states, characterized by the presence of σ_2 and σ_6, in the 90° layers. In particular three values of the biaxiality ratio λ_{12} have been investigated, equal to 0, 1 and 2, always referred to the stress state in the transverse layers. The damage onset and evolution, in terms of 90° cracks nucleation and propagation, were monitored by means of a FLIR SC7600 MW infrared camera and by in situ eye observations with the help of a internal lighting system. Figure 2 shows the testing and acquisition systems (a and b) and an image obtained from the lock-in analysis (c), showing the presence of multiple cracks in the 90° plies.

Figure 2: Testing system (a, b) and lock-in image (c)

Finally it is important to underline that, even if only tension and torsion loadings are externally applied, a stress component in the fiber direction (σ_1) takes place in the 90° oriented plies, due to the orthotropy of the material. It reaches the maximum value in tension and compression in correspondence of the internal and external diameter of the 90° layers respectively, and it is about the 4% of the applied transverse stress σ_2.
In addition, the presence of the fabric plies causes another stress component in direction 1 on the transverse plies. This contribution is also very low, and the maximum value of σ_1, considering both the above mentioned effects, is about -7% of the transverse stress (-2.8 MPa for the maximum applied load corresponding to 40 MPa of σ_2). Being these values very low, especially because they are in the fiber direction, they are neglected in the following analyses.

3 Experimental results and discussion

As already mentioned, being interested in the matrix-dominated fatigue behavior, the attention is focused on the nucleation of transverse cracks in the 90°, which are subjected to a biaxial stress state described by the parameter λ_{12}.
In figures 3, 4 and 5, ongoing fatigue test results are presented in terms of the maximum cyclic transverse stress on the 90° plies ($\sigma_{2,max}$) over the number of cycles spent for the nucleation of the first transverse crack N_f.

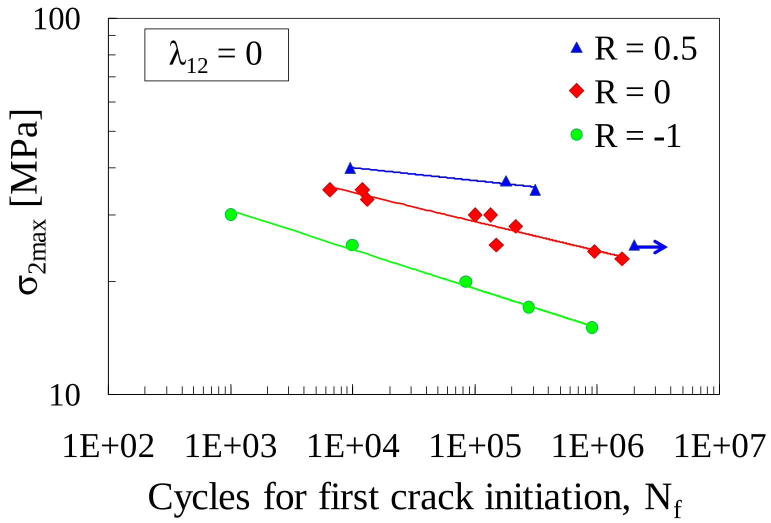

Figure 3: S-N curves for λ_{12} = 0 and R = -1, 0 and 0.5

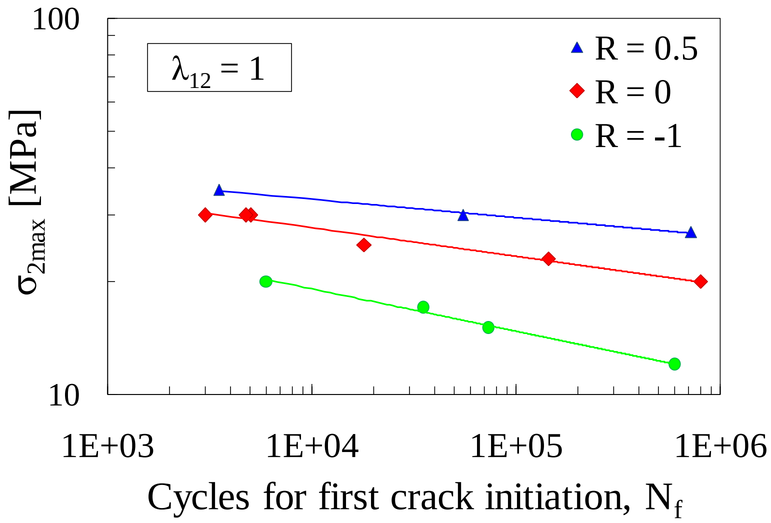

Figure 4: S-N curves for λ_{12} = 1 and R = -1, 0 and 0.5

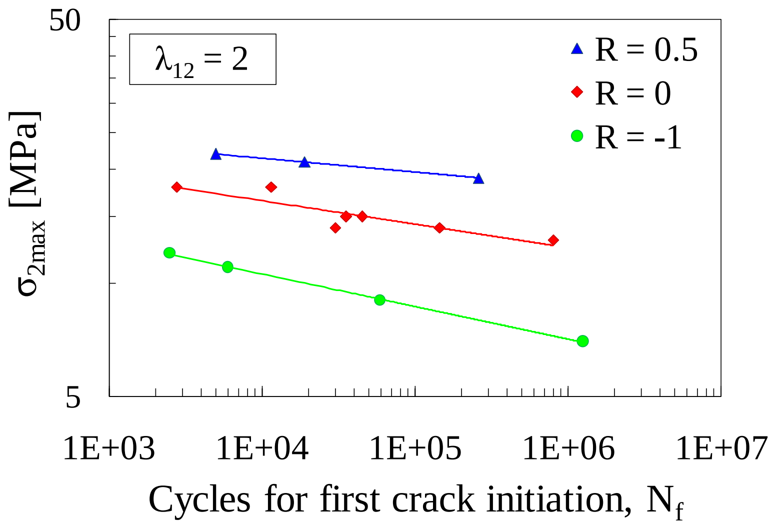

Figure 5: S-N curves for λ_{12} = 2 and R = -1, 0 and 0.5

A strong influence of the stress ratio is clearly evident for each value of the biaxiality ratio. In particular, for a given value of the maximum cyclic stress, a longer fatigue life is achieved for increasing values of R. In agreement with results from the literature [5, 6], the higher is the stress ratio, the lower is the slope of the fatigue curve, which can be expressed, in the investigated range of number of cycles, with the classical power law given in equation (2).

$$\sigma_{2\max} = K(R,\lambda_{12}) \cdot N_f^{a(R,\lambda_{12})} \tag{2}$$

The coefficients *K* and *a*, which are in general functions of R and of λ_{12}, are listed in table 2. Qualitatively, the effects of R for the three multiaxiality conditions investigated seem to be comparable, but more accurate and quantitative analyses have still to be conducted, in order to better clarify this point.
Finally in figures 6-8 the fatigue results are shown for fixed values of R, in order to highlight the influence of the biaxiality ratio. In each case an important detrimental effect can be observed for the fatigue curves expressed in terms of the maximum cyclic transverse stress, for increasing values of λ_{12}.

λ_{12}	R	a	K
0	0.5	-0.0344	55
	0	-0.0782	61
	-1	-0.1034	73
1	0.5	-0.0488	52
	0	-0.0753	55
	-1	-0.1127	54
2	0.5	-0.0373	30
	0	-0.0625	29
	-1	-0.0863	23

Table 2: coefficients of the S-N master curves expressed in equation (2)

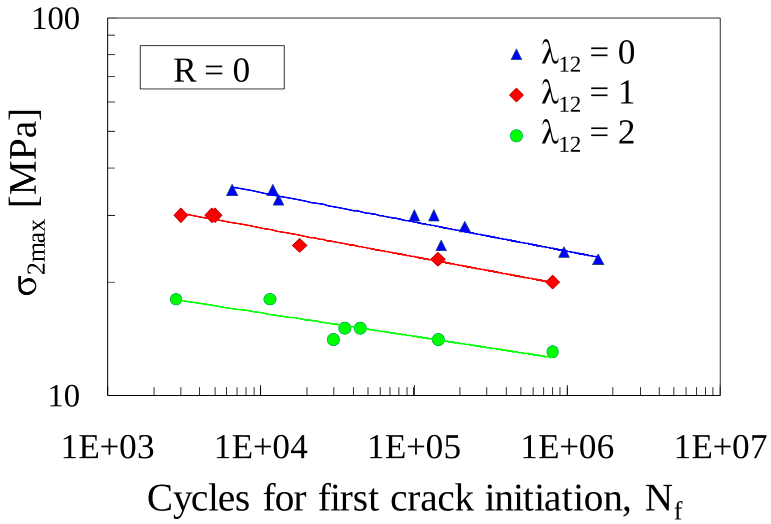

Figure 6: S-N curves for R = 0 and λ_{12} = 0, 1, 2

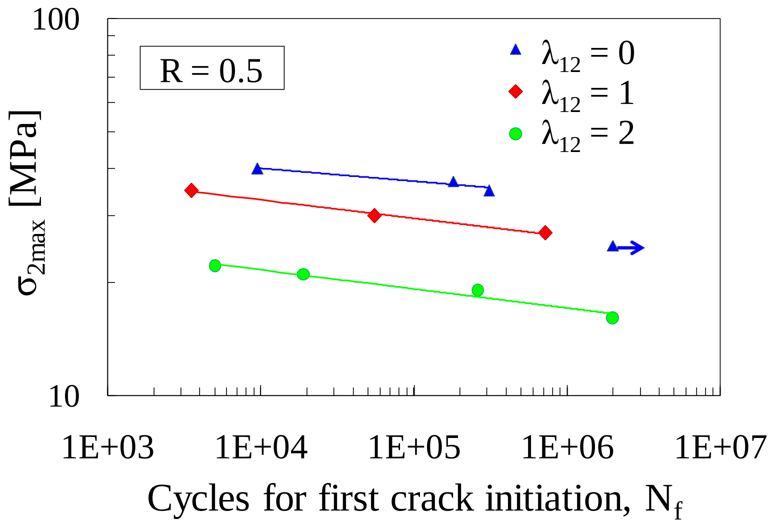

Figure 7: S-N curves for R = 0.5 and λ_{12} = 0, 1, 2

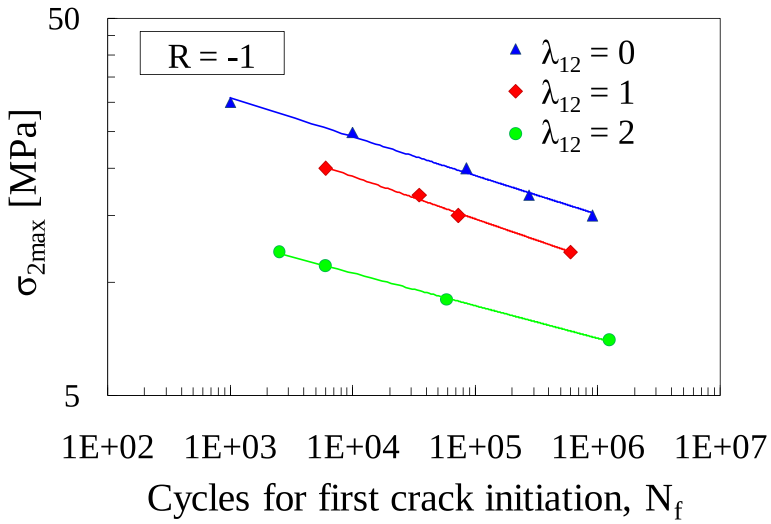

Figure 8: S-N curves for R = -1 and λ_{12} = 0, 1, 2

4 Conclusions

Fatigue tests have been conducted on glass/epoxy tubular specimens with lay-up [$0_F/90_{UD,3}/0_F$], subjected to combined tension/torsion loading, resulting in the stress components σ_2 and σ_6 on the 90° UD layers. Three different biaxiality conditions (λ_{12} = 0, 1, 2) have been investigated, and for each of them, different stress ratios R have been applied (-1, 0 and 0.5). Fatigue curves have been shown in terms of the maximum cyclic transverse stress over the number of cycles spent for the initiation of the first transverse crack on the 90° plies. Both parameter have been found to have a strong influence on fatigue life, in particular:

- for a fixed biaxiality ratio, a detrimental effect of a decreasing value of R has been highlighted, being the slope of the curves higher for lower value of R;
- for a fixed stress ratio the fatigue curves shifted from higher to lower values of the maximum transverse stress as the biaxiality ratio, i.e. the shear stress contribution, was increased.

It is therefore important to define a multiaxial fatigue criterion suitable to properly include this effects for the sake of fatigue life prediction. Concerning the influence of the multiaxiality, some ideas and encouraging results have been presented by in authors in [7], while some modeling efforts are planned in order to include the effect of the stress ratio.

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