Composites Science and Technology 99 (2014) 154–163

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

A damage based model for crack initiation in unidirectional composites under multiaxial cyclic loading

P.A. Carraro, M. Quaresimin *

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

ARTICLE INFO

Article history:
Received 31 January 2014
Received in revised form 8 May 2014
Accepted 9 May 2014
Available online 16 May 2014

Keywords:
B: Fatigue
B: Matrix cracking
C: Failure criterion
C: Multiscale modelling
Multiaxial fatigue

ABSTRACT

In the present work a criterion for the non-fibre (i.e. matrix or fibre–matrix interface) – controlled fatigue behaviour of composite unidirectional laminae subjected to multiaxial loading is proposed. The criterion is based on experimental observations of the damage modes occurring at the microscopic scale leading to the fatigue failure of a lamina. In particular two parameters have been identified as representative of the driving forces for the damage initiation, and they have to be used for design purposes depending on the local multiaxial condition. These parameters, i.e. the local maximum principal stress and local hydrostatic stress, are calculated from the local stresses in the matrix, obtained from Finite Element analyses of a fibre/matrix unit cell subjected to periodic boundary conditions. The application of the proposed criterion to fatigue data taken from the literature shows that only two scatter bands can be used to completely describe the fatigue response of unidirectional laminae under generic multiaxial stress states.

1. Introduction

Most of the static and fatigue failure criteria for unidirectional (UD) composites are based on macromechanical quantities such as the nominal stresses in the material coordinate system, which are often used in a polynomial expression describing the failure condition. Tsai–Hill and Tsai–Wu criteria are some classical examples for the static behaviour. An improvement to them is achieved by Puck's polynomial criterion [1], since it involves the macroscopic stresses lying on the fracture plane. However, the last mentioned approach is still a macroscopic and phenomenological criterion, thus not completely accounting for the actual damage mechanisms at the microscopic scale. With regards to the fatigue behaviour, some empirical criteria are also available in the literature, providing sometimes inaccurate predictions, as discussed in [2]. In addition, Kawai et al. [3] extended the Tsai–Hill polynomial criterion to fatigue, combining it with a continuum damage model to obtain a power law for the S–N curves, but without taking into account the different damage mechanisms occurring for different multiaxial conditions. Moreover, the description of the fatigue behaviour for both fibre and matrix-dominated response with only one equation seems not consistent from a physical point of view.

El-Kadi and Ellyin [4] proposed to use a polynomial expression involving the strain energy density components instead of the stresses, each contribution being normalised with respect to the static limit value. They obtained reasonable agreement with their own experimental data, but the limitations of this criterion are the same already reported for that of Kawai.

Before those attempts, Hashin and Rotem [5] proposed a polynomial criterion, separating the fibre and the matrix dominated behaviours, which have to be described with different expressions, to be used depending on which is the critical component in the composite lamina (fibre or matrix). In particular, for the matrix dominated behaviour they proposed to involve in a polynomial expression only the transverse and in plane shear stresses, weighted by means of fatigue functions to be experimentally calibrated.

The fibre and inter-fibre-related failure are treated separately also by the Puck's criterion based on the fracture plane concept. This criterion, initially conceived for the static behaviour, was extended to the case of cyclic loading by Sun and co-authors [6]. In spite of the merit of treating separately the fibre and matrix dominated behaviours, the criteria proposed in Refs. [5,6] still consider the macroscopic nominal stresses, involved in phenomenological expressions, without accounting for the damage mechanisms occurring at the microscopic scale, responsible for the lamina fatigue failure.

Concerning the non-fibre dominated behaviour, some efforts in the direction of considering the local stresses (or micro-stresses) acting in the matrix were published by Reifsnider and Gao in 1991 [7]. They used the Mori–Tanaka theory in order to evaluate

* Corresponding author. Tel.: +39 0444 998723.
E-mail address: marino.quaresimin@unipd.it (M. Quaresimin).

http://dx.doi.org/10.1016/j.compscitech.2014.05.012
0266-3538/

the average transverse stress and in-plane shear stress in the matrix, involving them in a criterion similar to that of Hashin, using fatigue functions of empirical derivation. In spite of the use of the local average stresses, this is still a phenomenological criterion, and it requires a large experimental effort for the model calibration.

In 1999 Plumtree and Cheng [8] developed a model based on the local stresses acting on the fracture plane, defined as the plane normal to the transverse direction. According to this definition of the fracture plane, the relevant stresses turned out to be the local transverse and in plane shear stresses only, calculated by means of Finite Element (FE) analyses of a fibre–matrix unit cell. In addition, reminiscent of Smith–Watson–Topper (SWT) criterion for metals [9], they accounted for the influence of the load ratio (ratio between the minimum and the maximum fatigue loads).

The aim of the present work is to define a damage based criterion, suitable to describe the non-fibre (i.e. matrix or fibre–matrix interface) dominated fatigue behaviour, in terms of crack initiation, of UD laminates subjected to multiaxial loading, characterised by the presence of the lamina stress components σ_1, σ_2 and σ_6 (see Fig. 1 for the definition of stresses).

It is very important to focus on the non-fibre-dominated behaviour because the fatigue life of a multidirectional laminate is characterised, since the early stages, by the nucleation of multiple matrix cracks in the off-axis plies (see Refs. [10,11] among the others). This phenomenon is responsible for the stiffness degradation of the laminate, and it is controlled by the matrix and fibre–matrix interface dominated behaviour of a single unidirectional lamina.

It is also known that the multiaxiality of the stress state strongly influences the fatigue behaviour of a UD lamina. Indeed, many works reporting off-axis fatigue test results show that different S–N curves, in terms of the global stress in the loading direction, are related to different off-axis angles [3,4,6,12,13].

In addition, an extensive experimental program was carried out by the present authors on Glass/Epoxy tubes subjected to combined tension/torsion loading, resulting in a stress state characterised by the presence of σ_2 and σ_6. Different S–N curves were found for different biaxiality ratios $\lambda_{12} = \sigma_6/\sigma_2$ [14,15]. In [15] the damage mechanisms occurring at the microscopic scale were also found to depend on the local multiaxial stress state, and this has to be accounted for in the definition of a reliable criterion for the description of the multiaxial fatigue behaviour of a UD lamina.

The model proposed here is indeed based on the damage modes experimentally observed in [15] and shown in the literature. Its application to a large bulk of experimental data shows a remarkable accuracy.

2. Mechanisms of fatigue failure

First of all, some preliminary considerations about the peculiarities of fatigue failure are needed. If a UD lamina is subjected to a cyclic loading condition leading to a matrix-dominated response, it fails without a visible, progressive damage [4,12,14]. This means that a stable crack propagation is never observed and, conversely, when a macro-crack (visible crack) nucleates, it propagates unstably leading the lamina to the complete fracture in just few cycles. Therefore, from several experimental evidences, it can be concluded that the matrix-dominated fatigue failure is controlled by the initiation phase, if the word "*initiation*" is referred to a macro-crack parallel to the fibres. However, at a microscopic level, a progressive and irreversible damage process has to take place during fatigue life, otherwise the decreasing trend of the fatigue S–N curves cannot be explained [16]. Thus, the cycles spent for the initiation of a macro-crack are controlled by the damage evolution occurring at the microscopic level. As a consequence, the definition of a multiaxial criterion consists in the identification of the damage mechanisms at the microscopic scale and the driving force for their evolution. In order to do that, the concept of the *local nucleation plane* is introduced in the following. As already mentioned, Puck's criterion is based on the hypothesis that the effective stresses to be considered as the cause of the static failure are the stresses lying on the fracture plane.

According to Puck, in the case of positive values of σ_2 and σ_6, the fracture plane is always the plane normal to the transverse direction (2-axis), and therefore the effective stresses are the global stress components σ_2 and σ_6. The importance of the fracture plane is emphasised also by Plumtree and Cheng [8], and also for them, in the case of an off-axis lamina, the stress components to be accounted for are σ_2 and σ_6 only, because they act on the plane normal to the 2-direction. The main merit of their criterion is that it considers the local stresses in the matrix, resulting from the concentrations due the presence of the fibres, instead of the global stresses.

It is important to point out that the fracture plane considered by Puck and by Plumtree and Cheng is actually the plane where final separation occurs and it can be therefore defined as *macroscopic fracture plane*. The actual plane where fracture initiates, in which the matrix micro-cracking and the damage process occur is instead not parallel to the fibres, and this is confirmed by the analysis of the fracture surfaces reported in [12,15] and by the experimental in-situ observations reported in [17], clearly showing a damage evolution generating inclined micro-cracks. In Fig. 2 the concept of the *local nucleation plane* is introduced, as the plane in which the micro-damage occurs, and can be identified in the onset, accumulation and coalescence of matrix micro-cracks which lead eventually to the formation of a macro-crack.

According to these observations the driving force for this kind of damage evolution can be identified in the stress components normal to the *local nucleation plane*. In the present work we assume the *local nucleation plane* to be perpendicular to the local maximum principal stress in the matrix. As a consequence, the effective stress to be considered is the Local Maximum Principal Stress (LMPS) in the matrix, which has to be calculated by considering the local

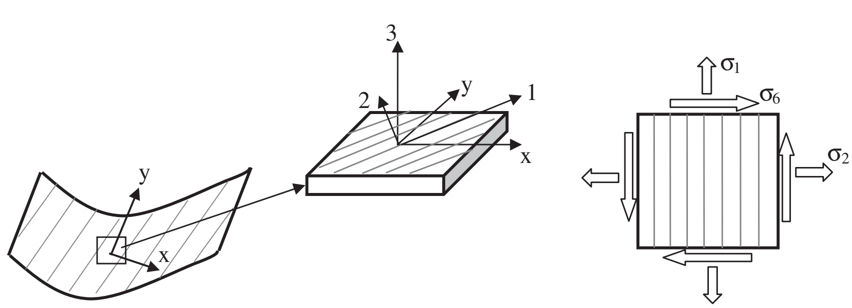

Fig. 1. Global and material coordinate systems, and stresses in the material coordinates system (1,2,3).