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Direct method for life prediction of fibre reinforced polymer composites based on kinematic of damage potential

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ABSTRACT

In this paper, a direct computational method of life prediction for fibre-reinforced polymers (FRP) is developed. This approach is based on a simplified direct method (SDM) which allows to predict the life from the stabilized damage state. The SDM is extended to the case of anisotropic continuous damage mechanics of FRP. It is shown that damage processes in composite material subjected to fatigue load can reach stabilized damage state. Damage state and thermodynamic forces associated with damage mechanisms at the stabilized state are related to life. Experimental validation was done on the standard glass-fibre/epoxy angle-ply and cross-ply laminate plates subjected to fatigue loading with different load ratios ($R = 0.1, 0.5$).

1. Introduction

Fibre-reinforced polymers (FRP) are widely used as structural components in many industrial sectors. In the design of composite structures, one of the important issues is fatigue assessment. It was reported and observed, by many experimental investigations, the complexity of fatigue phenomenon in FRP due to the following reasons: anisotropy and heterogeneity of material; multi-scale nature of damage processes in composite materials and their non-linear evolution during loading.

In order to model material response and be able to predict damage accumulation under service loading an appropriate constitutive model has to be defined with damage accumulation laws. There are many methods to model non-linear composite material response and among them three following groups can be distinguished: continuous [14], discontinuous [23] and multi-scale [39]. In this paper, we will focus mainly on models which are based on continuous methodology, also known as meso-scale methods which consider ply as homogeneous anisotropic material. In this type of modelling, composite is considered as a combination of continuous plies and interfaces, therefore, damage mechanisms are classified on two groups: inter-laminar and intra-laminar, respectively. The main idea is to define specific energy potentials for a ply and interface which depend on damage mechanisms. Then thermodynamic forces conjugated to damage could be defined as partial derivatives of the strain energy by damage variables. Efficiency of this type of modelling has been proved by wide range of applications in the majority of commercial and scientific software. One of the first works dedicated to non-linear material modelling of FRP composites that considered plasticity coupled with continuous damage mechanics (CDM) were [14] and latter [22] developed general theory. Even though the meso-modelling have been under intense development during last few decades it still is of interest for many research groups. Modelling of material non-linearity can involve the plasticity framework [37,34], continuous damage mechanics (CDM) [21,18,9] or coupled plasticity with CDM [36]. In [22,19,31,7] brittle damage models with strain softening behaviour were developed. On the other hand there are the discontinuous methods which are based on the fracture mechanics. These approaches have been highly developed for composites matrix cracking and delamination damage mechanisms in [20].

Developments in micromechanics have brought another stand point to the numerical simulation of the FRPs by involving the multi-scale formalism in order to reduce the number of phenomenological parameters of material. Many efforts have been given to define, represent and describe correlation between micro- and meso-damage phenomena [15,16]. This type of methods can efficiently combine meso-scale methods and micromechanics describe correlation between micro- and meso-damage phenomena [2].

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Despite of the extensive investigations and developments in constitutive modelling of the polymer composite material many questions are still opened. The World Wide Failure Exercise (WWFE) [10] was initiated in order to find out which failure theory is the most efficient one. The considered models are based on very different approaches. The results were so scattered, however some theories have been chosen as preferable among the others. Lately, few new models have been developed taking into account refined composite damage theory, such as importance of the three dimensional failure modes, which have brought a WWFE II. The results are discussed in [13]. But even the second organized exercise has left many questions to answer. Failure theories of the composites become heavily charged with different materials parameters. However, some candidates were chosen as best which gave least error between prediction and experimental results.

On another hand we have fatigue modelling. There are many models which are based on S–N curves and constant life diagrams which require plenty experiments [8,6]. Other approach is to involve meso-modelling (for instance [25]) then the total damage is consisted of: the static and fatigue parts. There are few drawbacks of this approach: the first is the relatively large number of the material constants and the second is the cycle-by-cycle calculation is necessary in order to evaluate damage [24].

In this work we will focus on the development of the direct method of life prediction which allows to avoid cycle-by-cycle simulation. Accepted assumptions have been justified by analyzing experimental data published for different composite materials. Main steps of the direct methodology have been correlated with fatigue phenomena in FRPs. The main emphasis placed on the stabilization effect of the damage processes. One of commonly used damage theories for composite materials, which is developed in [14], have been adapted here for the direct methodology. Finally, the proposed direct method is validated by comparing numerical simulations with experimental data for angle-ply and cross-ply composite plates subjected to different types of the fatigue loading ($R = 0.1, 0.5$). The experiments have been performed for the E-glass/epoxy laminate composite. Numerical results are in a good agreement with experimental data.

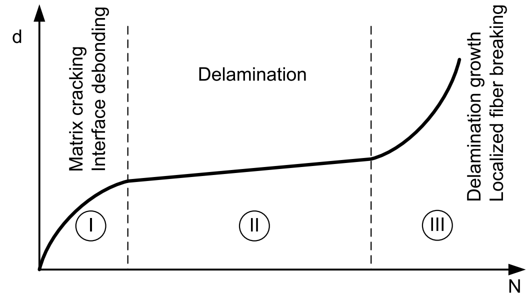
2. Fatigue phenomenon in FRP

Let us discuss damage evolution during fatigue process and non-linear mechanical response of the FRP materials.

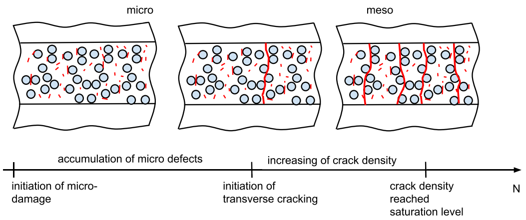
2.1. Damage accumulation and stabilization

The main damage mechanisms observed under fatigue loading are: matrix cracking, fibre/matrix interfacial debonding, delamination, fibre breaking and finally global fracture. The damage evolution is a non-linear function of number of cycles and has, in general, three characterizing patterns (Fig. 1a). At the beginning and near the end of fatigue life, damage growth is rapid, but for most of the life damage is gradual and linear [8]. The severity of each stage and total amount of damage depend on laminate stacking, material properties and loading conditions. The same three stages can be distinguished during evolution of the temperature field which is a consequence of the dissipation due to damage [29].

Stage I is characterized initially by fibre/matrix debonding which occurs depending upon the strength of the interfacial bond between fibre and matrix material. Then matrix micro-cracking process is initiated. The increase of crack density leads to micro-cracks coalescence and then to damage saturation. In Fig. 2a is shown the evolution of the crack densities in different layers of a tube under cyclic tension/compression [30]. The matrix damage saturation is a common process in laminates and damage state is given by the saturated matrix cracking and has been termed as *Characteristic Damage State* [28]. It is the starting point for those processes, which control the strength, stiffness and life of a laminate. The damage state can be accurately described and predicted. A schematic representation of damage initiation and growth process is shown in Fig. 1b.



(a) damage accumulation within cycles



(b) saturation of the cracks

Fig. 1. Schematic representation of fatigue damage in FRP.

Stage II is mostly characterized by the initiation and propagation of delamination which occurs near free edges or on the tips of transversal cracks [28,26]. During this stage, the damage can remain constant or gradually increase. It was shown that stiffness degradation is relatively higher for the lower stress levels in the case of [±45] composites under a loading ratio of $R = \sigma_{min}/\sigma_{max} = 0.1$ [6]. The linear dependency between normalized maximum stress and stiffness degradation is observed.

Stage III is the last stage of damage growth, all the damage modes would be developing rapidly in a fast-decreasing stiffness of the laminate. As the stress state reaches a critical value, fracture of the laminate would be initiated.

2.2. Mechanical response of FRP materials

Let us begin with classification of material response under cyclic loading which, basically, can have four kinds of behaviour [38]: *elastic response*; *elastic shakedown response*, when the elasto-plastic behaviour becomes purely elastic after a limited number of cycles; *plastic shakedown* (alternating plasticity), when the elasto-plastic behaviour becomes stabilized after a limited number of cycles, and the total deformation over a cycle converges to zero; *ratcheting response*, also called progressive deformation or incremental collapse, where the structure shows an elasto-plastic behaviour, but the total deformation over a cycle never converges to zero.

Here, we extend direct methods theory to the case of FRP for which anisotropic damage has to be taken into account. Some fatigue test data have been reported in [3,30] for different laminates as shown in Fig. 2. During fatigue tests, periodically block of cycles have been recorded to determine the strain–stress hysteresis loop (as reported in [3]) and to evaluate the modulus (also called fatigue modulus). Representative loops for a typical [±45] composite specimen are shown in Fig. 2d for a shear loading. It can be concluded that initially non-linear response becomes linear after a certain