

Fatigue Life Simulation on Fiber Reinforced Composites - Overview and Methods of Analysis for the Automotive Industry

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ABSTRACT

The need of weight reduction for fuel reduction and CO₂ regulations enforces the use of light-weight materials for structural parts also. The importance of reinforced composites will grow in this area. While the structural behavior and the simulation up to high strain-rate processes for those materials have been in the focus of investigation for many years, nowadays the simulation of high cycle fatigue behavior is getting important as well.

Efficient fatigue analysis for metals was developed by understanding the microscopic behavior (crack nucleation and initiation) and bringing it to the macroscopic level by combining it with the matching test data (SN curves etc.). Similar approaches can be applied to composite materials as well.

The paper gives a comprehensive review of fatigue simulation of fiber reinforced composite, based on the authors' experience in this field for different types of composites like random fiber reinforced to textile reinforcements, from detailed micro-structure analysis to efficient multi-scale algorithms, and from structural applications to detailed fatigue analysis.

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1. INTRODUCTION

This article will describe fatigue analysis in different types of composite materials like short fiber reinforced composite materials, unidirectional composite materials and textile composites. The need of weight reduction to achieve fuel reduction and meet CO₂ regulations enforces the use of light-weight materials for structural parts. Owing to its

excellent mechanical properties, light weight and ease of manufacturing, the use of composites is on the rise. There are expectations of higher use of composite materials in structural parts where the fatigue behavior is highly critical. However, the heterogeneous nature of composite materials makes durability analysis of composite structures a difficult task. A brief description of the challenges of structural design of composite materials is provided later in the article.



Composite materials usually consist of two phases- a matrix phase and a reinforcing fiber phase. Fibers commonly used for making composite materials are glass fibers and carbon fibers. Different matrices commonly used for making composite materials are epoxy, poly-propylene, poly-amide etc. The effective properties of a composite material depend upon a wide variety of factors like properties of the fiber and matrix, the architecture of the composite, the manufacturing process employed etc. Based on the architecture of fibers, we can divide composites into three major groups: i) Short fiber reinforced composites, ii) Continuous unidirectional composite and iii) Textile composites. Short fiber composites usually have fiber lengths in the range of 0.1mm to 25mm, randomly dispersed in the matrix. Unidirectional fibrous composites have long fibers arranged in one direction usually forming a ply (lamina), the arrangement of plies is designed to meet various requirements. Textile composites have a reinforcement formed by weaving, braiding, knitting or other textile technology, which is resin impregnated and cured.

Fiber reinforced composites usually perform better than conventional engineering materials with regards to life time in fatigue. The same, however, does not apply to the number of cycles for initial damage or to the evolution of damage [1]. There is however limited industrial experience in the automobile sector with composite materials and its fatigue behavior. Composite materials are heterogeneous and anisotropic, and their behavior is more difficult to predict than that of homogenous and isotropic materials such as metals. There are different types of damage that can occur in a composite material (e.g. fiber fracture, matrix crazing, matrix cracking, fiber matrix debonding etc.), the interactions between the damages and the different damage growth rates increase the complexity of the problem. A mode of failure which is passive, absent or not important in one type of composite may be very active and even critical in other types of composite materials; also, there are different dominant damage mechanisms for different loading directions. In metals, the first macroscopically recognizable damage (crack initiation) indicates failure and the stiffness usually remains the same throughout. However, composites suffer many micro-damages before final failure (see fig. 1); each micro failure usually leads to loss of stiffness and re-distribution of stress. Predicting every micro-damage and loss of stiffness is very difficult sometimes impossible; even when possible accounting for every event is usually not feasible due to the enormous computational efforts required.

The fatigue analysis of a composite material has a lot of other challenges, which were highlighted by Fong [3]. According to him, there is usually considerable confusion with regards to scale, there are at least three different scales while considering damage and fatigue i.e. micro (constituent level), meso (intermediate) and macro (component level); besides one is usually tempted to make easy but false generalizations regarding stiffness and strength during fatigue analysis. Most methods developed so far usually deal with single amplitude loading, single amplitude loading is

however quite exceptional in real life. Fatigue methods must be able to successfully account for the variation in amplitude loading and material degradation models must be built keeping in mind this requirement of real-life structures.

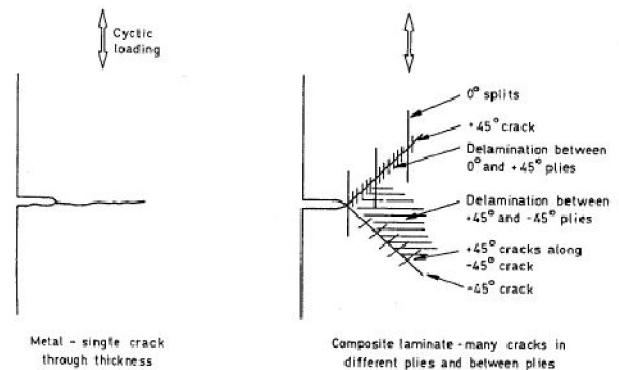


Fig. 1. Comparison of typical damage zones at notches in metals and composite materials [2].

Fatigue analysis could be done at three major scales namely micro, meso, and macro. Micro-scale analysis consists of studying and analyzing events occurring at the constituent level i.e. fiber, matrix and the interface between them, this method is usually quite accurate and can also predict the mode of damage, but requires computational resources which are usually not available to researchers and engineers. Macro-scale analysis takes into account damage and failure at the component level, with no or little regard to events occurring at the micro-level; this method though computationally cheap does not capture events at the micro-level and sometimes cannot predict the mode of failure. An intermediate level of analysis is the meso analysis. The scale of analysis is usually a matter of choice and requirement, with different scale suitable for different types of composite materials. Using a combination of scales (multi-scale approach) is also possible and is increasingly adapted for composite materials. An overview of fatigue analysis at different scales and for different types of composites is presented in this article.

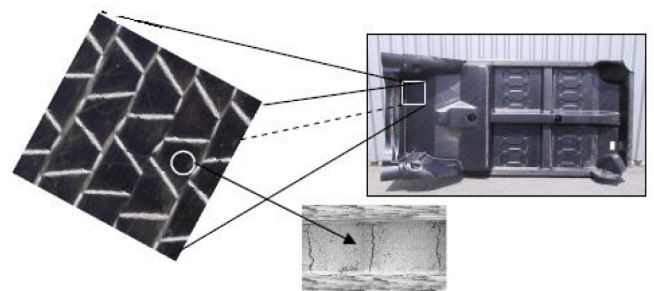


Fig. 2. The three different scales of analysis in a composite material; micro, meso and macro.

A brief outline of the article is as follows: First, in section 2 we present a feedback algorithm which has been quite

successful in modeling the material degradation in composites; this is named the cycle jump principle. In section 3, we describe a procedure for Meso finite element analysis of composite materials which can be implemented for both continuous and textile composites. In sections 4 and 5 we present fatigue methodologies for application in unidirectional composites and textile composites respectively. Section 6 includes a description of method for fatigue analysis of short-fiber composites. In section 7, we share some perspectives gained from fatigue analysis of metals and propose a method for analysis of composite materials which should lead to better understanding of fatigue in composite materials at the micro-scale and finally the article is summarized in section 8.

2. CYCLE JUMP PRINCIPLE

The implementation of the fatigue damage models in commercial fatigue and finite element software leads to two important but contradictory demands: [4, 5]

(A) The simulation should trace the complete path of damage and keep continuous track of continuous stress re-distribution.

(B) The number of cycles involved in typical analysis runs into hundreds of thousands of cycles, but finite element analysis (FEA) and fatigue software are expected to be fast and efficient.

Both these requirements are met in the fatigue analysis of composites using the concept of “Cycle Jump”. In this concept computation is done at deliberately chosen intervals, the stiffness degradation in these loading cycles is calculated and extrapolated at corresponding cycles.

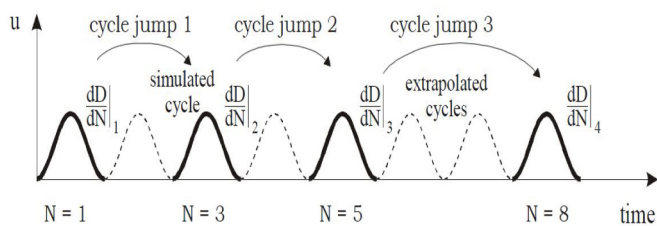


Fig. 3. The concept of cycle jump [4]

In finite element analysis this can be achieved by adding a state-variable NJUMP1 along with the necessary damage parameters, for each Gauss point. After looping over all the Gaussian points, a cumulative relative frequency distribution of NJUMP1 is calculated and the overall cycle jump NJUMP is determined as a fractile of the frequency distribution. The decision on the rerun of the FEA analysis is taken on the basis of upper threshold of increase in damage (dD/dN) in a local point. The increase in damage of all other points is then calculated as a function of the fractile distribution of NJUMP1. The lower the maximum increase in damage the more correct the calculations are, this obviously also leads to slower calculations. The cycle jump principle has been successfully employed in a variety of cases for textile and

continuous UD composites using SAMCEF™ finite element code. The computation time for fatigue analysis has been successfully brought down to reasonable limits which are comparable to components made of metals. The principle of cycle jump is yet to be tested in the context of random short fiber composites.

3. MESO FINITE ELEMENT FATIGUE MODELLING OF COMPOSITE MATERIALS

Meso-finite element modeling of a composite material in an FE model involves modeling of a composite material where each point on the macro level is the centre of a Representative Volume Element (RVE). The input properties are the elastic and fatigue properties of the uni-directional (UD) composite [6, 7]. This algorithm can be used successfully for both continuous uni-directional composite and textile composite; application for specific composite types is described later in the article. The requirement and the method employed for both the types of composite materials are described in detail in the next sections. The proposed method consists of the following steps:

(A) **Quasi-static loading is applied to the intact unit cell as the first half cycle.** (Fig -5.a) The unit cell is numerically loaded up to the magnitude of the maximum fatigue stress σ^{max} . Within this scenario, some material points are identified as failed by Tsai-Wu [8] damage criterion and their stiffness is degraded following an anisotropic damage model. The anisotropic damage model is achieved by assigning different damage tensors to the different damage modes, four different damage modes are taken into account for UD RVE failure. A pictorial representation of the damage modes is given in Fig 4; mode 1 corresponds to fiber rupture while modes 2-4 correspond to inter-fiber cracks. The degraded damage stiffness is then achieved by relating the new stiffness matrix Q^* to the initial stiffness matrix Q and the damage tensor corresponding to the mode of failure identified. The degraded properties are passed to the subsequent module.

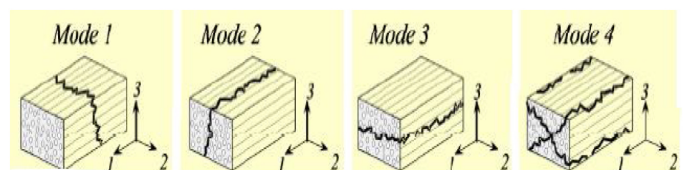


Fig. 4. The different modes of failure considered for failure of UD RVE [7]

(B) **Material points are being ‘worn out’ by fatigue.** The notion of NJUMP (described in previous section) facilitates the calculation over millions of fatigue cycles. Within a predefined number of load cycles, so called ‘load cycle jump’, the material points are continuously experiencing the fatigue weakening effect. Governed by the