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Fast fatigue life prediction of short fiber reinforced composites using a new hybrid damage approach: Application to SMC

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ABSTRACT

Industrial design of Short Fiber Reinforced Composites (SFRC) structures is subject to several compounding and processing steps of optimization. Moreover, these structures are often submitted to fatigue loading. Therefore, SN curves have to be established for each new composite formulation and for several type of microstructure involved in the real component due to processing. While these preliminary characterizations are time and money consuming, this paper propose a new hybrid methodology for fast fatigue life prediction. Moreover, both monotonic and fatigue behavior of SMC composites is essentially determined by local damage propagation. Therefore, the key idea of the proposed approach is to use a Mori and Tanaka based micromechanical model in order to establish an equation of state relating local damage rate to macroscopic residual stiffness rate. The generalization of this relation to fatigue damage multi-scale description leads to the SN curve fast determination of each considered microstructure. Very limited experimental characterization is required in such a way that SN curve could be established in just one day. Comparison between experimental and simulated Whöler curves highlights a very good agreement for several microstructure configurations in the case of a SMC composite material.

1. Introduction

For an efficient design of short fiber reinforced composites SFRC automotive components, several modes of failure have to be taken into account by the manufacturers. Particularly, fatigue loading may be considered as one of the most critical failure mode which strongly affects the component lifetime. In fact, poor knowledge and control of this mode of failure lead to specifications provided by the manufacturers which often need to be clarified. Moreover, the existent experimental databases, which should allow at least a pre-design, remain relatively poor especially for new material formulations. On the other hand, the development times become increasingly short and must also integrate the material formulation optimization. Several iterations are often necessary in order to identify the correct couple formulation-process suitable for each new application. Thus, it seems essential to build a rapid methodology of pre-dimensioning of composite structures allowing, within a short time, to identify the appropriate material formulation for each new automotive SFRC component. This methodology must therefore be pragmatic for industrial purpose. In the case of components submitted to fatigue loading, this is a critical issue because of the too long and too costly experimental campaigns needed to established SN curves.

Moreover, because of their heterogeneous architecture, anisotropic behavior and damage development, short fiber reinforcement composites SFRC structure design is very complex compared to homogeneous materials such as metals. Indeed, the mechanical properties of these materials were found to be greatly affected by their composition [1]: matrix type (thermoplastic or thermoset), volume fraction of reinforcing phase and their geometry and spatial distribution [2–5]. The diversity of composite material architectures and their complexity has for each application its own specificity. This wide variety of microstructures induces a significant dispersion of the mechanical properties, in particular under fatigue loading where the prediction of thresholds and kinetics of damage, their effect on the residual mechanical behavior and on the lifetime of the materials can present a very important challenge. These scattered results on composite S-N curves have been demonstrated by Barnard and al [6]. The authors admit the change of the damage mechanism as a result of microstructure variation and damage during the different stages of the fatigue process. They have also shown that there is a direct relationship between the strength statistical

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variation and the scatter observed in the composite S-N curves. One can expect that in the case of SFRC materials, this effect should be largely exacerbated because of the high variability of the microstructure generated during their molding process [7]. In fact, even for a single formulation, numerous different microstructures are present in a real SFRC automotive component. Consequently, a predictive modeling must imperatively integrate the microstructure as an input data.

Therefore, considering the complexity of the local mechanisms occurring during loading, the chosen approach must be based on a solid knowledge of these different phenomena. In the case of short fiber reinforced composites such as Sheet Molding Compound, it has been widely demonstrated that local damage must be a central focus of the design methodology [1,8]. Unlike thermoplastic based SFRC, non-linear behavior due to matrix visco-plasticity does not have to be taken into account at ambient temperature and low frequency.

However, in the case of fatigue behavior, environmental and loading conditions effects (temperature [9], stress ratio [10,11], cycling frequency [12,13]) are considered to be of first importance. Thus, the chosen methodology should be able to be adapted to predict the lifetime of these materials under these various complex conditions. On the other hand, fatigue damage and failure behavior of SFRC materials appears to be a very complicated and various process. Mainly, the existing predictive fatigue models for SFRC are generally classified into three categories [1,14]; empirical, based on S-N curves; phenomenological, based on residual strength or on residual stiffness evolutions and finally micromechanical, based on microscopic damage mechanisms description.

Great efforts have been expended to develop new methods allowing reducing substantially cost and time dedicated to characterization of fatigue behavior [15–21]. L. Jegou and al. proposed a new approach [17] based on the temperature measurements. An energetic fatigue criteria, identified from measurement results, is obtained from only one single microstructure in order to predict the fatigue curve from the heat build-up curve. The duration of the whole procedure is less than two days. Yann Marco and al [18] proposed in another recent paper a similar approach by relating the fatigue lifetime to the crack population evaluated from interrupted fatigue tests and the energy dissipation for a Natural Rubber compound filled with carbon black. This approach [17–21] proposes an efficient Wohler curves prediction based only on thermal measurements and an energetic criterion and has been applied on a wide variety of thermoplastic polymers and rubbers [21]. However, the authors do not specify if this approach should be effective in the case of thermoset polymer or their composites presenting a lower thermal effect especially with low operating frequency and amplitude [22].

Jain and al [23,24] have proposed an approach based on a micromechanical model relating the macroscopic damage state in quasi-static loading to that reached as a certain point on a givenS-N curve. The authors propose a methodology allowing prediction of the S-N curves for other composites microstructures from the knowledge of the so called "master curve" which corresponds to the S-N curve established for one specific microstructure taken as a reference. However, the proposed methodology is based on the experimental statement that for similar number of cycles to failure, the difference in the loss of stiffness curves for different microstructures is not significant and can be statistically treated as being the same. Experimental evidence shows that, in the case of SMC materials, the loss of stiffness kinetic and its critical value just before failure is strongly dependent of the microstructure.

In this paper, a hybrid modeling approach is proposed. In order to take into account microstructure and damage effect, this model is based on a Mori and Tanaka predictive approach integrating a damage criterion at the microstructure scale. This model is identified in the case of a simple tensile loading for one single microstructure and is able to predict the monotonic mechanical response for each other microstructure. Then, using the output of this micromechanical model, a phenomenological formulation allows a rapid evaluation of the SN curve for different other microstructures. In order to drive the model, limited experimental data from laboratory tests are needed.

In the next section, the different steps of the proposed methodology are presented. Then, the micromechanical damage model is described until the identification of an equation of state applicable under monotonic tensile loading. The model is applied to a SMC composite material which is presented together with the experimental methods and results in the third section. The last section is dedicated to write an equation of state under fatigue loading to be solved in order to establish SN curves with minimum experimental data. The methodology is validated for three kinds of microstructure: a Randomly Oriented SMC (RO) and a Highly Oriented SMC under two fatigue loading directions (HO-0° and HO-90°).

2. Presentation of the new hybrid methodology

In this study, we are looking for a pragmatic methodology of rapid design of SFRC materials submitted to fatigue loading. This approach is suitable for thermoset based composite materials such as SMC composites for which non-linear behavior is essentially attributed to damage phenomenon. Therefore, this is a stiffness based model based on a micromechanical approach in which a damage criterion in introduced at the local scale. This model is presented in the next section. Further development of our approach will be proposed in the case of thermoplastic based composites for which matrix non-linearity should be taken into account.

The key idea of this approach is to introduce the output of an accurate micromechanical damage model into a phenomenological approach. Such a hybrid model combines the advantages of both micromechanical and phenomenological approaches: In one hand, the proposed methodology is pragmatic and well adapted to industrial design. On the other hand, our model keeps the reliability of the micromechanical approach through the description of local damage evolution. As it has been shown in previous studies [25,26], the non-linear behavior of standard SMCs submitted to quasi-static, dynamic or fatigue loading is mainly governed by the same phenomenology: fibre-matrix interface failure development. Under tensile or fatigue loading, accumulation and propagation of local damage lead to a progressive loss of stiffness which can be considered as a good indicator of damage state. Therefore, independently of the loading type, any local damage state can be directly related to the corresponding degraded macroscopic properties. In other words, the relation between local damage and macroscopic loss of stiffness should be understood as an intrinsic relationship. Consequently, it is obvious to consider that fatigue damage and tensile damage can be described by the same type of relationship.

Previous experimental studies [25–28] showed that final failure appears when the micro-cracks density reaches a certain critical value. This critical value can be represented as a local damage rate, $\frac{d}{d_c}$ where d is related to the current amount of fibre-matrix interface damage and d_c is a critical value. In SMC composite materials, one can assume that the pseudo-delamination phenomenon which always appears just before failure [29,30], takes place when the local damage rate is equal to 1. Therefore, one can consider the local failure criterion as:

$$\frac{d}{d_c} = 1 \tag{1}$$

In the proposed fatigue life prediction model, this criterion is supposed to be an intrinsic characteristic of the material independently of the applied loading type: quasi-static or fatigue. Physically, it means that failure always occurs for the same critical amount of local damage independently of the loading history when the non-damage volume of the material becomes too small to withstand the applied load. Consequently, when the critical local damage rate is reached, coalescence of micro-cracks rapidly leads to final failure. Therefore, one can consider that the failure criterion described in equation (1) can be