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Fatigue lifetime modeling of oxide/oxide composites

Orianne Sally[a,b,c]*, Cédric Julien[b], Frédéric Laurin[b],Rodrigue Desmorat[c], Florent Bouillon[a]

[a] SAFRAN Ceramics, Rue de Touban, Les cinq chemins, F-33185 Le Haillan, France
[b] ONERA -The French Aerospace Lab, 29 avenue de la Division Leclerc, F-92322 Châtillon, France
[c] LMT , ENS Paris-Saclay / CNRS / Université Paris-Saclay, 61 avenue du Président Wilson, 94235 Cachan Cedex, France

Abstract

The assessment of service life of composite thermo-structural parts is a primary issue for the aeronautic industry. To this end, a unified damage model for woven composites undergoing both static and fatigue loadings is presented here. Its specificity resides in its rate damage evolution law, which enables to predict the behaviour of the material under cyclic or random fatigue loadings.

Keywords: Composites; damage model; fatigue lifetime.

1. Introduction

Due to their excellent mechanical properties at high temperatures, ceramic matrix composites (CMC) are often selected for applications in hot part of engines. However, non-oxide composites are severely deteriorated under operating conditions in turbomachines. Consequently, for some engine components subjected to moderate thermo-mechanical loadings (between 800 and 1000°C), oxide/oxide CMCs are potential candidate materials in regard to their interesting trade-off between mechanical properties, thermal stability and cost. Hence, it seems necessary to

* Corresponding author. Tel+33 1 46 73 45 78; fax: +0-000-000-0000 .
*E-mail address:*Orianne.sally@onera.fr

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develop efficient computational strategies for the design of composite parts submitted to both static and fatigue loadings.

To fulfil these objectives, a specific damage model for this material has already been developed under static solicitations [1] at Onera but remained to be extended to fatigue loadings. To our knowledge, there is no model in the literature to predict the fatigue lifetime of oxide/oxide materials. A Damage Model for Polymer Matrix Composites, developed at Onera (named ODM-PMC), was recently extended to cyclic fatigue loadings [2] and validated through comparisons with the available experimental data. Nevertheless, some composite parts would be subjected to real fatigue solicitations, not necessarily cyclic, during all the lifetime of an aircraft. Fatigue models using the so-called "kinetic damage evolution law" [3]–[5] allow getting rid of the cycle notion and to handle random complex loadings.

This work presents a unified damage model for woven oxide/oxide composites undergoing static and complex fatigue loadings. The model, described at the woven ply scale (mesoscale), is presented in section 3. The numerical results are then compared to the available experimental data in section 4.

2. Damage model

A model, based on the Continuum Damage Mechanics, was firstly developed to describe the behaviour of oxide/oxide woven ply laminates under static loading.

The model, defined at the woven ply scale, is thermodynamically consistent and is relevant to predict the damage and the failure of oxide/oxide composite structures.

The formulation of the present damage model, is based on previous works performed at Onera and LMT Cachan for composites with polymer matrix or ceramic matrix [1]–[3], [6], [7], but takes into account the specificities of the studied oxide/oxide woven composite material. It is assumed that the observed non-linearities are only due to the damage mechanisms. The macroscopic behaviour, expressed in Eq. 1, derives directly from the Helmholtz free energy.

$$\underline{\sigma} = \underline{\underline{C}}^{eff} : (\underline{\varepsilon} - \underline{\varepsilon}^{th}) - \underline{\underline{C}}^{0} : \underline{\varepsilon}^{r} \quad \text{with} \quad \underline{\underline{C}}^{eff} = \left(\underline{\underline{S}}^{0} + \sum_i d_i \, \underline{\underline{H}}_i \right)^{-1} \tag{1}$$

where $\underline{\sigma}$ is the stress tensor, $\underline{\underline{C}}^{eff}$ the effective elastic stiffness tensor taking into account the effects of the three different damage mechanisms, $\underline{\underline{C}}^{0}$ the initial elastic stiffness tensor, $\underline{\varepsilon}$ the total strain tensor, and $\underline{\varepsilon}^{th}$ the thermal strain tensor. In the present approach, the effects of damage mechanisms (in-plane transverse cracking in the matrix in the warp or weft direction and yarn/matrix deboundings) on the macroscopic behaviour are translated by an increase of the initial elastic compliance $\underline{\underline{S}}^{0}$ with an additional term ($\sum d_i \, \underline{\underline{H}}_i$), that depends on the damage variables and the corresponding effect tensors, describing the effects of an open crack on the effective stiffness. Finally, the specific strain tensor $\underline{\varepsilon}^{r}$ accounts for the residual strains after unloading, due to the evolution of the different damages.

2.1. Damages occurring during static loadings

Ben Ramdane [1] demonstrated experimentally that the damage in this material is mainly oriented by the microstructure. Therefore, under plane stress hypothesis (representative conditions of the available tests), only two scalar damage variables, d_1 and d_2, are introduced in the model, corresponding respectively to the in-plane damages within the matrix oriented in the warp and in the weft directions.