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Damage initiation and structural degradation through resonance vibration: Application to composite laminates in fatigue

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ABSTRACT

The definition of failure is fundamental to the characterisation of fatigue strength of components and structures and is often expressed as a percentage of stiffness degradation. This article proposes a new method to capture damage initiation and structural degradation during a fatigue test, by exploiting resonance vibrations. The method entails monitoring dynamic parameters, including the phase angle between excitation and response, which suddenly changes as soon as the overall stiffness changes as a consequence of damage. In this paper, a theoretical approach based on equations of motion is presented in order to describe the possible scenarios in which a component undergoes structural degradation. In the proposed approach, an abrupt change in the time history of the stiffness of the component is assumed and analysed in both the quasi-static case at low excitation frequencies and the dynamic case, when the excitation frequency is close to the resonance frequency. The resulting analytical solution shows that any small stiffness variation is amplified by the dynamic response of the component as a large phase change, even when it is too small to be captured by the quasi-static response. The idea is successfully applied to capture the initiation of delamination in CFRP laminates, and the relative S-N curve to initiation is drawn. The experimental evidence of a critical event in the fatigue life of a component is found both in the dynamic phase response and in the base acceleration. The critical event is captured from a sudden change in the dynamic parameters of the structure as soon as a delamination is initiated. Thermography, C-scan and micrograph confirmed that the onset of delamination occurs at the moment of the critical event, after an initial stage of microcracking.

1. Introduction

The definition of damage initiation is one of the most discussed topics in fatigue behaviour of components. It is widely agreed that the nucleation of damage in a pristine component can be a large part of its total fatigue life, but unfortunately its characteristic features are particularly difficult to understand and therefore predict. For this reason, the crack initiation is usually related to a subjective critical crack dimension. For different materials, as recalled by Bhattacharya et al. [1], the critical crack dimension could vary from a microscopic scale of few micrometres [2] to a few millimetres, depending on the type of components or structures and their applications. The lack of a generally accepted definition of crack initiation can be put down to (i) the difficulty of measuring cracks on the length scale of nanometres and (ii) the practical significance of having measured a crack of such small size.

As the definition of crack initiation is not unique for homogeneous materials, such as metals, it is even harder to find a general definition of initiation for composite materials, where damage is identified by the complex status of the material rather than by a single crack. Since first studies on fatigue of composites, it was clear that the damage development comprised a series of interacting phenomena, leading to continuous and diffuse structural degradation. Reifsnider in 1980 addressed the main issue in understanding fatigue behaviour of composites, i.e. the absence of a "well-defined damage state, something that replaces a single crack in homogeneous materials" [3]. He proposed a sequence of steps for the damage development that can be summarised as (i) crack nucleation in off-axis plies and saturation at the Characteristic Damage State, (ii) crack coupling due to the interface debonding

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when the crack tips reach the interfaces, (iii) formation of a wider damaged region by the previous process, (iv) crack growing through the thickness by crack coupling and (v) final fracture of fibres in the direction of the load.

According to this sequence, the damage initiation should be defined as the first nucleation of a transverse crack in an off-axis ply. However, initiation could be defined at different levels, from the microscopic molecular observation level to the macroscopic structural observation level. As demonstrated by Caiulo and Kachanov [4], there is no direct correlation between clustering of microcracks (microscopic observation level) and stiffness reduction (structural level). In fact, since the stiffness reduction is a property of the entire structure, it averages the crack distribution over the volume, resulting in being insensitive to clustering. Therefore, a more practical definition of initiation is the one given by Salkind [5] as “the time required to form a crack of detectable size”. Lomov et al. [6] considered the damage initiation as the occurrence of a crack that connects many debonded fibres and that can be captured by an increase in the energy content of acoustic emissions. Quaresimin [7] used 0.3 mm as the value of the crack to be considered detectable by a microscope, justifying that small changes in the initial crack length have a small effect on the fatigue life, within the scatter of the experimental data in any case. On the other hand, O’Brian proposed a new damage tolerance philosophy for composite materials [8], assuming the existence of matrix cracks throughout the off-axis plies, and the onset of delamination being predicted by a strain energy release rate threshold. This threshold can be obtained by running several tests at several high loads, whereby the onset of delamination is always unstable and easily detectable because of catastrophic change in stiffness. In Refs. [9], Sims reviewed the fatigue testing methods beginning with the concept of failure criterion for composites. He identified the need for a failure criterion based on loss of stiffness, as recommended by standard procedures [10], that could vary from 5% to 20%, depending on applications. It is evident, once again, that there is no universal criterion to define the damage initiation.

May and Hallett [11] investigated the incorporation of damage initiation into a cohesive element model. In this case, model calibrations were made for mode I and mode II in accordance with the previous work of O’Brien et al. [12] on transverse tension fatigue and May and Hallett [13] on damage initiation in shear fatigue, respectively. For mode I it was observed that initiation and final failure occurred within a short period of time, thus it was assumed that initiation corresponded to the actual separation of the specimen in two pieces. For mode II, the Short Beam Shear (SBS) test and the Double Notched Shear (DNS) test were evaluated and compared for their potential in providing data for S-N curves to damage initiation. Both tests have some shortcomings and limitations, but it was concluded that the DNS test was more reliable in determining damage initiation.

Use of resonance vibration for in-situ monitoring of structural degradation and residual stiffness of components during fatigue testing is not new [14–16]. Since first studies in the 50’s [17], the vibration fatigue testing method has become standard practice [18,19], exploiting the resonance conditions to perform quick tests to a high degree of accuracy, even in the Very High Cycle Fatigue (VHCF) regime, up to the gigacycle [20].

In the present work it is shown how a measurement of the resonance frequency or a direct measurement of the stiffness could be too coarse to capture the occurrence of damage initiation during the test. The aim of this article is to present a more sensitive method for monitoring structural degradation and consequently damage initiation. Here, damage initiation shall be defined as a critical event that changes the rate of structural degradation for a given excitation level. In other words, an event that can abruptly change the distribution of the stiffness of a component under fatigue loading conditions.

2. Understanding structural degradation in a dynamic environment

Let us consider a prismatic beam of length L and section S subjected to longitudinal natural vibration.

The forces acting on an infinitesimal segment of the beam in Fig. 1 having density ρ and length dx can be written as

$$\frac{\partial F}{\partial x}dx = \rho S dx \frac{\partial^2 u}{\partial t^2}, \tag{1}$$

where F is the force, u is the displacement and t is the time. By considering the definition of the elastic modulus, one can write

$$\frac{F}{S} = \sigma = E\varepsilon = E\frac{\partial u}{\partial x}. \tag{2}$$

Combining Eq. (1) with Eq. (2) yields to

$$\frac{\partial^2 u}{\partial x^2} = \frac{\rho}{E}\frac{\partial^2 u}{\partial t^2}, \tag{3}$$

where the ratio between the density ρ and the Young's modulus E is the inverse of the velocity of propagation of the strain wave in the beam, ν.

For a free-free beam the solution of the n^{th} mode of vibration gives an angular frequency ω that can be written in the form

$$\omega = \frac{n\pi}{L}\sqrt{\frac{E}{\rho}}, \tag{4}$$

Eq. (4) for the first mode ($n = 1$) reduces to

$$\omega = \frac{\pi}{L}\sqrt{\frac{ESL}{\rho SL}} = \pi\sqrt{\frac{k}{m}}, \tag{5}$$

where $m = \rho SL$ is the mass of the beam and $k = ES/L$ is the axial stiffness. One can relate this example to a simpler Single Degree Of Freedom (SDOF) system. For our scope of showing the high sensitivity of the phase in capturing any change in the stiffness of the structure, it is necessary to add a damping force to the system. A typical lumped parameters SDOF system is given by a mass-spring-damper arrangement, where a mass is connected to the ground by a spring and a damper in parallel. The mass is excited by a force acting directly on it, and the response is measured as the absolute displacement of the mass. This SDOF system is well known. We shall focus on the solution of the forced response. The modulus of the receptance $\alpha(\omega)$ and the phase shift $\phi(\omega)$ can be described by

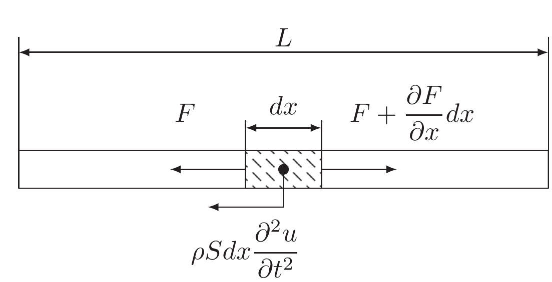

Fig. 1. Forces acting on an infinitesimal beam segment subjected to longitudinal natural vibration.