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Review

Fatigue reliability analysis of viscoelastic structures subjected to random loads

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ABSTRACT

This paper is devoted to the investigation of the possibility of increasing fatigue life of engineering structures subjected to multiaxial random loads by applying constrained viscoelastic layers. The rationale for such study is the fact that as the addition of viscoelastic materials provide decreased vibration amplitudes, it becomes important to quantify the increase of reliability that can be obtained. Moreover, despite the fact that many multiaxial fatigue damage criteria applicable to undamped structures exist in the literature, none of them is adapted to deal with the problem of estimation the fatigue damage in structures incorporating viscoelastic damping, since they must conveniently account for the frequency- and temperature-dependent behavior of the viscoelastic material. Due to the nature of the stress state of the considered problem, the fatigue damage is assessed by using Sine's global criterion. After presenting the theoretical aspects, the numerical fatigue damage analyses of a three-layer sandwich plate treated by passive constrained damping layer are addressed, and the main features of the methodology are discussed.

Contents

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1. Introduction

In the development of many types of engineering products, it is observed an increasing demand for durability, reliability, safety and comfort. As a result, during the early design phases or during the analysis of existing systems, analytical or numerical procedures should be used in order to predict their fatigue life over a desired range of loading conditions. As an example, long-span bridges that have performed well under wind loads for decades have been recently found to have accumulated fatigue damage resulting in cracking of structural components [1].

More recently, much effort has been devoted to the study of efficient passive control techniques to be applied to medium- to high-scale structures to mitigate undesired levels of vibration. Among these, passive control techniques based on the use of viscoelastic materials present some advantages such as inherent stability, effectiveness in broad frequency bands and moderate development and maintenance costs [2–4]. In practice, those materials can be applied either as discrete devices, such as translational mounts and rotational joints [5], or surface treatments known as Passive Constraining Layer Damping (PCLD), and Active Constraining Layer Damping (ACLD) [2]. However, the incorporation of the viscoelastic behavior into the finite element (FE) models and the numerical approaches for resolution of the resulting equations of motion are particularly relevant aspects of the modeling procedures since for viscoelastic structures the stiffness matrices depend on frequency and temperature. Among the standard rheological and more complex models [2] intended to represent the dynamic behavior of viscoelastic materials, the complex modulus approach has been adopted in this paper, since it is adequate for frequency response analyses, based on which the fatigue damage analysis of structural components is to be performed.

In the quest for fatigue damage analysis, many authors such as Sines [6] and Crossland [7] found-out that the stress-based multiaxial damage criteria based on the equivalent shear stress amplitude (amplitude of the square root of the second invariant of the stress deviator) and an equivalent endurance limit (function of the hydrostatic stress and material parameters) seem to be better suitable to estimate the high-cycle fatigue life of engineering structures, since the equivalent shear stress amplitude is considered as a major parameter to control the crack initiation. Thus, several multiaxial fatigue criteria have been developed for performing fatigue damage analysis of undamped structures, as reported in references [6–14]. However, few studies have addressed the problem of estimating the probability of failure of structures incorporating viscoelastic damping devices, which motivates the study reported in this paper.

In particular, Pitoiset and Preumont [9] have contributed successfully to the use of the Crossland and Matake criteria in the frequency domain. However, the proposed approach has some limitations such as being confined to zero mean random loads and narrow band stress responses. You and Lee [8] and Papadopoulos [14] have shown that the critical plane criteria are more appropriate when the principal stress directions are fixed. However, the performance of fatigue damage criteria is questioned since the non-proportionality is not taken into account for ductile materials [10]. Weber [13] has observed by experimental results that none of the tested criteria is fully satisfactory but the Sines' criterion seems to give better predictions. Thus, Lambert et al. [10], based on the experimental results described in reference [13] have proposed a probabilistic approach of the Sines' global criterion by considering the random nature of the stress state and load phase shifts on fatigue damage analysis. This probabilistic model is employed in this paper in order to characterize the statistical distributions of Sines' damage indicator of a viscoelastically damped structure subjected to stationary random excitations, and to assess the probability of non-failure. The main goal of the study is to propose and appraise a finite-element based procedure enabling to quantify the increase of reliability that can be achieved by the use of surface viscoelastic damping devices. The practical interest, from the engineering perspective, is obvious.

One of the difficulties which are dealt with arises from the fact that the typically high dimensions of large-scale FE models of industrial structures incorporating viscoelastic materials make the numerical fatigue damage analysis of such systems very costly, sometimes unfeasible. This fact motivates the use of a special condensation method based on the use of a constant (frequency- and temperature-independent) enriched reduction basis which takes into account *a priori* information of the applied loading and the viscoelastic damping forces [15].

In the remainder, after the presentation of the theoretical foundations of the methodology, the description of a numerical study of the fatigue reliability of a rectangular plate treated by PCLD subjected to a stationary random transverse load is addressed. The numerical study is carried-out to evaluate the influence of the viscoelastic materials on the stress responses, on the fatigue damage distributions, and on the probability of non-failure of the structure.

2. Review of the FE modeling of plates treated with viscoelastic constrained layers

In this section, the model of a moderately thin three-layer sandwich plate finite element, which can be frequently found, for example, in aerospace systems, is summarized, based on the original developments made by Khatua and Cheung [16] and implemented by de Lima et al. [15]. The inclusion of the frequency- and temperature- dependent behavior of the viscoelastic material is made by using the so-called *Elastic-Viscoelastic Correspondence Principle* [2], according to which, for a given temperature, the structural matrices are first generated for specific types of finite elements (rods, beams, plates, etc.) assuming that the longitudinal modulus and/or the shear modulus (according to the stress state assumed) are constant (independent on frequency and temperature). Then, after the finite element matrices are constructed, the frequency–temperature dependency of those moduli is introduced according to the complex modulus approach combined with the *Frequency–Temperature Superposition Principle* [2,17].