Finite Elements in Analysis and Design 119 (2016) 1–14

Contents lists available at ScienceDirect

Finite Elements in Analysis and Design

journal homepage: www.elsevier.com/locate/finel

Full Length Articles

Benefits of metamodel-reduction for nonlinear dynamic response analysis of damaged composite structures

Saber Mahmoudi*, Frédérique Trivaudey, Noureddine Bouhaddi

FEMTO-ST institute, UMR 6174, Department of Applied Mechanics, University of Franche-Comté, UBFC -24 rue de l'Épitaphe, 25000 Besançon, France

ARTICLE INFO

Article history:
Received 11 November 2015
Accepted 3 May 2016
Available online 26 May 2016

Keywords:
Composite structure
Nonlinear dynamics
Damage detection
Model reduction
Component mode synthesis
Artificial neural networks

ABSTRACT

In this paper, a novel method for damage prediction and dynamic behaviour analysis of laminate composite structures is proposed and investigated. The dynamic behaviour of transversely isotropic layers is expressed through elasticity coupled with damage using a phenomenological macro-model for cracked composite structures made of polymer reinforced with long glass fibres. The damage is fully described by a single scalar variable whose evolution law is expressed through the maximum dissipation principle. Using the classical linear Kirchhoff–Love theory of plates and considering the damage-induced nonlinearity, the obtained nonlinear dynamic equations are solved in time domain using a Newmark algorithm. To reduce the computational costs, a metamodel-reduction for damage localization and quantification is proposed where the Artificial Neural Networks (ANNs) and Craig–Bampton reduction methods are combined. Extracted stresses from finite element analysis are used as input for a feed-forward ANNs to estimate the damage severity. The Craig–Bampton reduction method is introduced as a Component Mode Synthesis (CMS) to investigate the case of assembled structures locally damaged. Numerical simulations show that the damage modifies significantly the dynamic properties restricted to the eigenfrequencies reduction. The designed feed-forward ANNs was verified and it provides promising results regarding severity and location of the damage. Moreover, the trained ANNs provide a quick response for damage level prediction in online procedure which permits to significantly reduce the computational costs.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

Over the last decades, composite materials are increasingly incorporated into the high-tech products and they are more used now on vital components. As an example, the ratio of composites with respect to the total structural mass in Airbus A380 aircraft is about 25% and it becomes 53% in the A350-XWB aircraft. According to the security requirements, the new uses of composite materials require a greater confidence in these materials. This leads to the knowledge of damage mechanisms that may occur in these heterogeneous materials. Indeed, the composite structures are subjected to one or more forms of damage such as matrix cracking [1], fibre fracture [2] and delamination [3]. They evolve gradually resulting in the mechanical degradation of the structure properties and the modification of its mechanical behaviour. The behaviour of damaged composites has been the subject of several investigations. The degradation phenomena are usually modelled on a micro or meso-scale approach while the mechanical behaviour is modelled on a macro scale approach. The micro-scale approach for modelling these degradations are characterized by its ability to properly reproduce the experimental observations closer to the degradation by giving it a geometric representation. However, this modelling is limited to the elementary volumes and it does not allow the simulation of complex structures [4,5]. The meso-approach comes between the micro and macro-scales. It is related to the scale of the ply. It does not give a geometric representation of the damage but its characterization is represented through a local evolution of the material parameters in damaged regions. A first meso modelling is proposed in the works of Kachanov [6] and Rabotnov [7], wherein the damage is introduced as the degree of reduction in the structure resistance and the loss of its rigidity. The interest of this approach is the ability to describe the influence of the damage on the deformation, which provides an indirect tool for measuring it via the concept of effective stress. This latter is the stress that must be applied to undamaged volume element to get the same deformation as that caused by the stress applied to the damaged volume element [8]. In the one dimensional case, the damage can be defined as the relative difference of the two stresses and it can also be expressed by the decrease of the

* Corresponding author. Tel.: +33 3 81 66 60 10.
E-mail addresses: saber.mahmoudi@femto-st.fr (S. Mahmoudi), frederique.trivaudey@univ-fcomte.fr (F. Trivaudey), noureddine.bouhaddi@femto-st.fr (N. Bouhaddi).

http://dx.doi.org/10.1016/j.finel.2016.05.001
0168-874X/© 2016 Elsevier B.V. All rights reserved.

Young's module [9]. In the case of laminates, the initiation and evolution of damage is different from one layer to another and the overall behaviour of such structures is described from the behaviour of each layer. In this context, a meso model of damaged laminates has been developed in [10] to simulate the gradual evolution of damage under any loading, based on the introduction of three scalar variables. These variables are associated with an unidirectional layer and they are assumed to be constant in the thickness direction.

These forms of damage may not be visible from surface, but they may have a significant effect on the structure stiffness, its strength and its life-time. Therefore, the damage mechanism is the subject of several studies in the literature, especially with regard to techniques of detection, quantification and localization of the damage. There are several methods of damage detection in composite materials. Among the most commonly used, there are methods based on acoustic emission [11,12], the methods based on infrared thermography [13,14]. These methods are costly and they need to take the structure out of service. Indeed, Vibration-based detection methods are also widely used [15–17], and can be used as damage assessment methods because the damage can be quantified and localized. Since each eigenfrequency and its corresponding mode shape are affected to different extent depending on the location of the damage, a sufficient knowledge of the curvature of multiple mode shapes is required to have a rigorous localization of damage [18], which makes the method costly in the case of complex structures. The damage identification can be considered an inverse problem since it is determined with respect to the shift in stiffness. This inverse problem is nonlinear and an analytical solution is not obvious to get. Thus, for reasons of simplicity, advanced identification techniques based on artificial intelligence methods have been widely studied such as genetic algorithm [19,20] and artificial neural networks [21,22].

Since the high numerical costs related to the computing time and data storage in numerical simulations of nonlinear finite element problems, several studies are oriented towards developing reduced models having a limited number of degrees of freedom called Reduced Order Model (ROM). Many ROM have been proposed, such as the Guyan method [23], hierarchical modeling [24], domain decomposition [25,26]. Component mode synthesis (CMS) is one of ROM methods. It is based on the domain decomposition concept. The overall domain is divided into subdomains or components where a basis function is associated to each component. Craig–Bampton method [27], that will be used in this paper, is well adapted to the problems of assembled structures that have local non-linearities. In addition, Artificial neural networks (ANNs) can be used to reduce the numerical costs via establishing a simple relationship between the input and output variables. They are defined as computational models whose design is very schematically inspired from basic operating concept of biological neurons [28]. They represent an efficient tool for solving the nonlinear inverse problem. ANNs are widely used in various application fields which can be summarised into pattern recognition or classification, modelling and prediction. By the self-determination of their relationship between input and output, ANNs present an interesting self-adjustment capability that allows complex problems to be dealt with. Another key strength of ANNs is generalisation. Once the network is trained and its parameters determined, it can be able to accurately deal with inputs which were not present in the training data. Therefore, ANNs represent a promising metamodelling technique, especially for data sets having non-linear relationships as the case of damage detection and quantification problem. Several researchers used ANNs to detect, localize, and quantify damage in monotonic and composite structures. Sahin et al. [29] proposed a damage detection algorithm using a combination of changes in eigenfrequencies and curvature mode shapes as inputs to ANNs for damage detection and prediction of its severity. Zhang et al. [21] used numerical data from a finite element model of a delaminated composite beam and eigenfrequencies from modal testing as inputs for ANNs in order to predict the interface, lengthwise location and size of delamination. Xu et al. [30] proposed an adaptive multiplayer perceptron (MLP) for crack detection in anisotropic laminated plates where the only displacement response on the plate surface is provided to the MLP as input. A literature reviews in which the ANNs are used in the damage detection is provided in [31,16].

In the current study, a novel metamodel is proposed for predicting the damage and the dynamic behaviour of laminates made of unidirectional orthotropic layers of a polymer matrix reinforced with long fibres. The proposed stress-based metamodel is based on the combination of artificial neural networks techniques and component mode synthesis method for nonlinear analysis of damaged complex composite structures. Using a phenomenological modelling of cracked structures, the dynamic behaviour of the composite structure is expressed through elasticity coupled with damage. The damage is reported by a single scalar variable which is a value deduced form the stiffness loss. Its location and level depend on the stress state in the structure. The incremental linear dynamic governing equations are obtained by using the classical linear Kirchhoff–Love theory of plates. Then, since the damage induces nonlinearity, the obtained nonlinear dynamic equations are solved in time domain using a Newmark unconditionally stable algorithm. For assembled structures, when the damage is located only in some regions, the full finite element model is decomposed into components. Thereby, Craig–Bampton method is used for modelling a nonlinear fine-scale damaged components, connected to linear dynamic models of the remaining components, which can be reduced keeping their initial properties. Therefore, a metamodel is proposed based on the ANNs, and it is coupled with the CMS method for assembled structure, to estimate the dynamic response and the damage level.

Several numerical simulations have been performed, first to investigate the damage effect on the dynamic behaviour of the structure and second to provide a data set consists of a tripled stresses and their corresponding damage level. The highlights of this paper are: (i) the proposed method permits to obtain the precise location of the damaged areas and allows the reporting of the propagation and evolution of the damage in the structure with a high accuracy, (ii) as a result of its two reduction levels (ANNs and CMS), the proposed metamodel-reduction reduces significantly the computational costs and it can be useful for structural health monitoring methods.

2. Modelling of damaged dynamic behaviour

2.1. Bilateral damage model

For laminated composite structures, fibre rupture generally occurs in the final phase of layer rupture whereas matrix cracking is considered as the first damage mechanism and presents a common defect in laminated composites. Under a static or dynamic load, the micro-cracks evolve and grow leading primarily to the degradation of the structure stiffness through the decrease of the transverse elastic Young's modulus. In this paper, the studied structures are made from a thin layer of polymer reinforced with long glass fibres oriented with respect to $\vec{e_1}$ direction as depicted in Fig. 1(a) where the micro-cracks are parallel to the fibre direction. Boubakar et al. [32] deduced, through experimental analysis, that the damage in the polymer matrix depends on the micro-cracks opening modes ($M1$) and ($M2$) as shown in Fig. 1(b).

Download English Version:

https://daneshyari.com/en/article/513725

Download Persian Version:

https://daneshyari.com/article/513725

Daneshyari.com