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A model updating method for hybrid composite/aluminum bolted joints using modal test data

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ABSTRACT

The aim of this paper is to present a simple and applicable model for predicting the dynamic behavior of bolted joints in hybrid aluminum/composite structures and its model updating using modal test data. In this regards, after investigations on bolted joints in metallic structures which led to a new concept called joint affected region (JAR) published in Shokrollahi and Adel (2016), now, a doubly connective layer is established in order to simulate the bolted joint interfaces in hybrid structures. Using the proposed model, the natural frequencies of the hybrid bolted joint structure are computed and compared to the modal test results in order to evaluate and verify the new model predictions. Because of differences in the results of two approaches, the finite element (FE) model is updated based on the genetic algorithm (GA) by minimizing the differences between analytical model and test results. This is done by identifying the parameters at the JAR including isotropic Young's modulus in metallic substructure and that of anisotropic composite substructure. The updated model compared to the initial model simulates experimental results more properly. Therefore, the proposed model can be used for modal analysis of the hybrid joint interfaces in complex and large structures.

1. Introduction

The accurate prediction of structural dynamic characteristics such as the natural frequencies and damping ratios in order to vibration control and evaluating their performance in a dynamic situation is a significant aspect in the design of aerospace structures. Prediction and determination of the dynamic characteristics of the aerospace structures which are often composed of several parts or substructures depends on capability and ability of proper modeling of the joints interfaces. The joints usually cause a local increase in damping and decrease in stiffness of the structure and thus change its dynamic characteristics [1]. Therefore, accurate modeling of the joint regions is a necessary process to determine the dynamic behavior of large structures (composing of thousands of parts).

Nowadays, the increasing use of composite materials in combination with metallic parts in modern engineering structures has led to a new structural concept called hybrid structures [2]. In general, the hybrid metal-composite structures are divided into three main groups including steel/composite, titanium/composite and aluminum/composite. The first group are used mainly in navy structures [3–6], military vehicles [7], and also heavy transport vehicles [8]. The second group is usually

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used in aeronautical structures [9,10]. The third group sometime is used in electrical isolators [11], and electronic devices [12] but their major applications are in aircraft structures [13]. An important necessity in designing of these kinds of structures is the joining of two different materials with distinguishable properties which needs special considerations. The joining of metal-composite substructures may be executed by adhesive materials or mechanical fasteners or even a combination of two approaches. The bolted joint of metal parts with polymer matrix composites is a most common joining process in hybrid constructions for aeronautics and space applications [14].

A proper understanding of complex physics of the bolted joints interface region in composite structures and modeling of their performance and investigating their response in different loading conditions have been a concern for researchers for decades. In this area, numerous studies on the mechanically fastened joints of composite materials and structures can be found in review papers [15,16].

Investigating the parameters such as the joint geometrical dimensions [17–19], the effects of stacking sequences on joint strength [20–23], bolt preload [17,23], bolt diameter [18,24], the number of bolts [25,26], the bolt head type [27], the clearance between the bolt and hole [28–30], the geometrically nonlinear effect [31] and material nonlinearity [32], the effects of high temperatures [33], hysteresis effects [34] and the combined effect of bolted and bonded joints [35] under different loading conditions are attractive topics for researchers in this area. However, few studies have been done regarding the dynamic behavior and dynamic characteristics of the joints in composite structures [36,37]. Moreover, few studies have been focused on the design and analysis of joints in hybrid aluminum/composite structures. In these researches, topics such as the secondary bending effect [38], load transmission capacity [39], and failure mechanism [40,41] have been investigated.

Due to increasing utilization of the hybrid structures in aircraft industries, accurate modeling of hybrid joint interfaces in order to investigate their effects on structural dynamics characteristics is going to be more important than ever. But modeling of joints in hybrid structures is a difficult process, because, in addition to intrinsic complexity of joint interfaces [42], there exist many uncertainties in modeling of behavior and properties of composite materials and complexities of failure mechanisms in them [43]. Moreover, a detailed 3-D modeling of joints may lead to a considerable computational runtime and cost; for this reason, evaluation of the failure mechanisms in bolted composite structural joints have been based on experiments at past decades [44].

On the other hand, analytical methods in dynamic modeling of joints in addition to complexity usually do not yield accurate results [45]. The difficulty is not here, how to model but the question is what should be modeled [46]. Considering the joint mechanics and parts interfaces accurately, including nonlinear effects, slipping, energy lost and probably noncontinuous behavior effects requires overcoming some current limitations and better understanding of joint physics and parts interfaces [42]. Therefore, developing the parametric models for the uncertain structural parts including supports and joints have been an interesting subject for the researchers for a long time. In this regards, a simple and accurate parametric model is necessary to simulate dynamic behavior and especially, modal analysis to determine dynamic characteristics such as the natural frequencies and damping ratios.

In general, two approaches are used for extracting dynamic characteristics of complex structures which are experimental (modal testing) and numerical (finite element analysis) methods. Today, structural dynamics analysis is mostly carried out by using commercial FE analysis software. These software can yield only an estimation of eigenvalues of the system due to simplifying procedures in simulation process and also due to lack of proper elements in order to precise modeling of some critical regions such as the bolted joints. Therefore, the predicted structural dynamics behavior using FE models are different from their observed behavior in practice [47].

Parameterization of some critical structural parts such as supports and joints and assign some proper values to these parameters is an effective solution in modeling process, although, parameterization of joints is a difficult procedure [47]. Output data of the analytical model such as the natural frequencies and mode shapes are often sensitive to little variation of these parameters and incorrect values of the parameters may lead to the mistake results. Using the experimental results associated with a model updating technique is considered as a well-known method for modifying these parameters. the parameters can be longitudinal stiffness (EA), bending stiffness (EI) or they can be geometrical dimensions or elastic properties like young modulus and poison ratio of a specified region of structure such as joints.

FE model updating is, in fact, a method to refine and correct the incorrect assumptions in modeling process via adjusting the model parameters based on the experimental results [47]. Model updating methods are divided generally into two main groups including direct and indirect [48,49]. Nowadays, the indirect or iterative methods are used largely based on a sensitivity analysis [50]. In this approach, some special parameters of the model can be modified such that an objective function containing a difference between the predicted values by finite element method and measured data are minimized. Therefore, the experimental methods are introduced as an alternative approach to the development of mathematical models of the structural joints, i.e., by creating an initial theoretical model and using experimental data it is possible to improve the model behavior [1]. The modal testing results are used in order to correcting the model parameters or model updating. The updated model can provide a more accurate simulation of the joints [51].

According to a literature review, the lack of adequate researches in the area of hybrid structure vibrations can be observed. The aim of this paper is to propose a simple, accurate and proper model for simulation of dynamic behavior of bolted joints in hybrid aluminum/composite structures, such that, the errors due to incorrect modeling of joints in predicting natural frequencies can be minimized. Therefore, "doubly connective layer" model is proposed in this paper for finite element modeling of joint interfaces in hybrid structures and then the model is updated using genetic algorithm.