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Nonlinear dynamic analysis of harmonically excited debonded sandwich plates using finite element modelling

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ABSTRACT

Nonlinear dynamic aspects of a rectangular simply supported sandwich plate with a central penny-shaped debonded zone subjected to harmonic loading have been studied by using the finite element analysis within the ABAQUS code. In order to accurately predict the response of the debonded sandwich plate to harmonic loading, contact-impact and sliding conditions along the damaged skin-to-core interface were imposed in the model via the penalty contact algorithm in the framework of an implicit integration scheme. The relevant qualitative parameters such as frequency response curves, phase portraits and Poincaré maps were extracted from time history signals calculated by the finite element analysis for sandwich plates with and without debonded region. The results of the both plates were compared, to specify the effects associated with the presence of debond on the forced vibrations of the sandwich plate. A wide range of forcing frequencies was applied to illustrate various nonlinear responses occurring in the debonded plate's dynamics. A considerable influence of contact events within the debonded region on the global dynamic response of the debonded plate subjected to periodic loading was found out. The predictions performed also showed that the finite element model applied would be useful for nondestructive evaluation of defects in composite sandwich plates.

1. Introduction

Over the past few decades sandwich panels have become a popular structural component in many industrial applications where dynamic loading prevails. The reason thereof is superior properties of sandwich structures over the conventional metallic counterparts. In general, a sandwich panel is a special type of laminates where a layer made of a more flexible and lightweight material (core) is located between two strength and stiff face sheets (skins). This structural concept provides high bending stiffness and strength of the sandwich structure without adding much weight [1]. However, the bonded interface between too dissimilar materials of the core and skins is the weakest point of such structures. Wrong manufacture processes or unfavorable service conditions can induce the appearance of a partially debonded region along the skin-to-core interface. Experimental observations [2] have shown that the presence of debond in sandwich panels affects their integrity and reduces their overall stiffness and strength and, as a consequence, alternates their dynamic responses. Therefore, in order to provide reliability and durability of sandwich structural elements in service, the modelling of dynamic behavior of sandwich panels with an existing debonded zone is highly required at the design stage.

The dynamic behavior of intact sandwich panels is the subject of extensive studies, e.g. [3–5] among many others. In contrast to this, papers reported on the dynamic behavior of sandwich panels with debond are less presented in the literature. Apart from the nonlinearities mentioned for the dynamics of perfectly bonded sandwich beams, plates and shells, the vibrations of those debonded structural elements are accompanied by additional types of nonlinear phenomena. Contact and impact, and friction between the detached surfaces of skin and core are main among others. Even assuming that the influence of nonlinearities others than contact-impact and friction are negligible, this is true for most of real structures vibrating at a forced frequency that is far from a resonance frequency, simulations of the dynamic behavior accounting for contact and friction are a challenging problem yet in the structural analysis.

One of the possibilities to tackle the dynamic contact-impact problem arising in cracked structures is the reducing of an underlying complex structure to a simple model with one or several number of degrees of freedom [6]. Such spring-mass-damper models were successful to reveal nonlinear responses of composite

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beams with interlaminar damage such as sub- and superharmonic resonances, cascades of period doubling bifurcation and the existence of chaotic motion, e.g. it can be found in [7–10]. Additional studies of complex phenomena in vibro-impacting systems such as a grazing of periodic orbits, a period-adding sequence and the coexistence of different attractors for the same control parameters with complex basins of attraction can be found in many recent papers, e.g. [11–14]. While the oscillator models, used in those studies have shed some light on the nonlinear phenomena of cracked structures they suffer from the lack of information about a spatial presentation of both the deformation modes and distributions of interlaminar stresses within the cracked region. Thereby continuous models of vibrating structures damaged by cracks, explicitly describing the interaction between the detached segments, are still highly required.

Since a sandwich plate can be referred to a kind of laminate, the debonded zone within it can be treated as an equivalence to a delaminated region, hence, analytical, numerical and experimental approaches developed for studying dynamic delamination effects (see [15] for an overview) can be, in essence, adapted for the vibration analysis of debonded sandwich plates. The split spanwise region approach and the constrained model envisaging the same movement of separated segments for an across-the-width debonded region was used to find an analytical solution for the free vibration analysis of a debonded sandwich beam with anisotropic composite laminates skins and an orthotropic honeycomb core in [16]. The authors presented parametric studies of free vibrations depending on properties of face sheets, core and debonded zone geometry. In [17] a strip element method technique was utilized to simulate the propagation of wave fields in a sandwich plate containing non-bonded regions located symmetrically above and below the core. For the sake of simplicity, the problem was reduced to a two dimensional beam model and the debonded regions were modelled as a rectangular flaw spreading through the core thickness. The unconstrained debonding model which permits the overlap between the debonded surfaces of skins and core was adopted in that research. Based on this approach an analytical model was developed by Kim and Hwang in [18] to study effects of the symmetrically located debonds on reduction in the flexural bending stiffness and natural frequencies of honeycomb sandwich beams with laminated skins. The results obtained analytically were, then, compared with experimental observations. Recently, the same analytical formulation has been applied and verified through appropriate experiments to evaluate free vibration characteristics of sandwich beams with a single and two symmetrical debonds at the interface between the carbon fiber reinforced plastic (CFRP) face sheets and honeycomb core in [19]. A semi-analytical approach relying on the high order sandwich panel theory was developed in [20] for studying a transient dynamic response of a simply supported sandwich beam with a single debonded region. A set of nonlinear governing equations of motion of the debonded beam accounted for explicit contact conditions at the debonded interface without using contact mechanics formulations. The system of equations was numerically solved by using the Newmark-beta method for integration over time.

The versatility of the finite element method (FEM) for solving complex topological and multi-physical problems has made it a popular means in investigations of debonded sandwich panels. In [21] both the FEM analysis and experimental investigations were performed to obtain natural frequencies and a steady state response of a honeycomb sandwich plate with aluminum skins containing a circular debonded zone at the center. The developed three-dimensional FE model of the plate used a hexahedron element with eight nodes. The assumptions of free debonding model were accepted at the debonded region. Finite element predictions of vibration and buckling of laminated sandwich plates with skin-to-core interface layers damaged at different levels using a refined higher order shear deformation theory were performed in [22]. The interlaminar imperfection was modelled by a linear spring layer model implemented into an elaborated 6-node triangular finite element. Using the spring model definition, pointwise spring finite elements within a three-dimensional FE model applied for the free vibration analysis were introduced into a debonded region of a sandwich plate to avoid interpenetration between the detached face sheet and core in [23,24]. This model allowed authors to evaluate the influence of debonded zones' size and form as well as their location and number on natural frequencies and mode shapes of sandwich plates with different core types and subjected to different boundary conditions. However, no contact interactions have been taken into account. Kwon and Lannamann in [25] have investigated transient dynamics of a debonded sandwich plate using a FE model where time dependent contact conditions at the damaged interface were simulated. A kinematic node-to-node frictionless contact algorithm was utilized. A much more sophisticated FE simulation of the contact-impact phenomenon taking place between thin detached part and remaining beam was carried out in [26]. To obtain correct numerical results in a stationary case of forced motion, authors applied the surface-to-surface penalty based frictionless contact algorithm with contact damping within the LS-DYNA code. A nonlinear dynamic analysis of sandwich plates containing a post-impact zone involving core fracture and interfacial debond under impulse and harmonic loads was done in [27]. In those simulations the surface-to-surface contact definition and kinematic contact algorithm within the ABAQUS code were used to model the contact phenomenon during forced oscillations. Although the global dynamic response of the sandwich plates was examined, the contact impact phenomenon existing between the detached skin and core was not investigated in detail in that paper. A detailed analysis and simulation of nonlinear dynamics of a simply supported rectangular sandwich plate with a penny-shaped debonded zone has been carried out using the ABAQUS/Explicit code in [28]. While this research provided a formulation based on the formalism of continuum mechanics of the underlying elastodynamic problem involving contact and friction laws, the numerical studies were there rather demonstrative examples than investigations on the nature of nonlinear forced dynamics.

Thereby, it follows from the literature search results that suitable three-dimensional models to simulate the dynamics of sandwich plates weakened by the partially damaged skin-to-core interface are still high required for investigating nonlinear effects occurring in them. In this article, a nonlinear dynamic behavior of simply supported rectangular sandwich plate with a central penny-shaped debonded zone subjected to harmonic excitations is studied. While the spatial discretization of the debonded sandwich plate is the same as in [28], an alternative solution technique is utilized within the ABAQUS code in the current work. In contrast to the explicit solution methodology used in [28], an implicit direct integration scheme exploiting the Hilbert–Hughes–Taylor operator with controllable numerical damping and the Newmark formulae is applied here. Also, the penalty method and the return mapping algorithm, which are consistent with the implicit time stepping scheme, are used for resolving local contact and friction problems, respectively. Based on this numerical algorithm, nonlinear features exhibited by the vibrating debonded sandwich plate are investigated in detail. To detect nonlinearities existing due to the "breathing" behavior of the debonded zone, response signals of both the debonded sandwich plate and the same intact plate predicted numerically are compared. The estimations of spectral components in time history signals as well as comparisons of phase orbits, frequency response curves and Poincaré sections are used to evaluate the nonlinearities appeared.