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Geometrically nonlinear transient analysis of delaminated composite and sandwich plates using a layerwise displacement model with contact conditions

Miroslav Marjanović [a,*], Djordje Vuksanović [a], Günther Meschke [b]

[a] Faculty of Civil Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia
[b] Institute for Structural Mechanics, Ruhr University Bochum, Universitaetsstraße 150, 44801 Bochum, Germany

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ABSTRACT

In the paper, a computational model for the transient response of laminated composite and sandwich plates with existing zones of partial delamination, subjected to dynamic pulse loading is proposed. Laminated composite and sandwich plates are modeled using the extended version of the Generalized Laminated Plate Theory. For the numerical solution, the finite element method with layered finite elements is used. Delamination between individual layers is considered as discontinuities in the displacement field using Heaviside step functions. Since the status of delaminated layers may change in dynamic loading conditions, leading to the so-called "breathing" phenomenon, contact conditions allowing for the opening/closing of delaminated layers are proposed. Nonlinear kinematics in the sense of small strains and moderately large rotations is accounted for according to the von Kármán assumptions. The material of the individual layers is assumed as orthotropic and linearly elastic. The governing spatial–temporal partial differential equations are integrated in time by means of the implicit Newmark's method. After verification of the proposed model for intact plates, the effect of the size and the position of embedded delamination zones on the transient response of geometrical nonlinearity of composite and sandwich plates is investigated numerically by means of a number of numerical applications.

1. Introduction

Laminated composites play an important role in the design and construction of aircrafts, wind turbines, ships, cars and many other parts in mechanical and civil engineering. These engineering materials allow for high strength and stiffness at a relatively low weight. Examples are carbon-fiber, glass-fiber, or fiber-reinforced polymers (FRPs), which include carbon-fiber reinforced plastic (CFRP) and glass-reinforced plastic (GRP). A major limiting factor for the lifetime of these structures is the presence of delamination, resulting from the different fabrication induced faults in the joining of laminas. For example, riveting and saw cuts induce large stress concentrations and local plastic deformations, which can lead to a local debonding of adjacent layers [1].

Another type of plate structures relevant for the proposed model are sandwich panels, i.e. structural members made of two stiff faces separated by an isotropic core. The low weight of sandwich panels was first exploited in the aircraft industry [2] and used also in civil engineering as light roof and wall panels, usually designed in the form of soft-core sandwich panels, which purpose is usually to provide the thermal isolation of buildings. Because of their position in the structure, sandwich panels are often exposed to dynamic forces such as turbulent wind loading.

The bond between the face sheets and soft-core in sandwich plate must remain intact for the panel to perform on the appropriate level. Consideration of existing interfacial damage often is relevant for the assessment of the residual lifetime of such structures [3]. This requires adequate computational models able to consider delamination of plates in dynamic loading environments. In case of dynamic loading conditions, it is of particular importance to understand the effects of delamination on fundamental dynamic characteristics such as natural frequencies and mode shapes. In their previous work [4], the authors have shown that the presence of embedded delamination seriously influences the dynamic characteristics of composite and sandwich plates.

The structural response of laminated plates can be accurately determined by the use of simple Equivalent Single Layer (ESL) laminate theories, especially for laminates with high length-to-thickness ratios [5]. In the case of thicker structural components,

* Corresponding author. Tel.: +381 11 3218 581; fax: +381 11 3370 223.
E-mail address: mmarjanovic@grf.bg.ac.rs (M. Marjanović).

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these theories are not adequate, since they give too stiff response because of simplifications associated with the classical plate kinematics. Example is First-Order Shear Deformation Theory (FSDT) based on Mindlin–Reissner assumptions, where transverse shear effects are taken into account by means of shear correction factors. In the case of laminated composite and sandwich plates, discontinuities in transverse shear strains at the interfaces between adjacent layers are significant, which are not accounted for in ESL theories. These limitations have motivated research on the refined plate theories. For the extensive overview of ESL plate theories, we refer to the monographs by Staab [6], Reddy [7] and Gay et al. [8], among other references.

The number of exact 3D elasticity solutions of the intact laminated composite plates is generally limited [9,10]. Various finite element families based on different laminated plate theories have been developed to obtain the numerical solutions for static or dynamic problems. Reddy [11] used finite elements based on the First-Order Shear Deformation Theory for geometrically nonlinear analysis of laminated composite and isotropic plates without consideration of delamination. Further, Ju et al. [12] divided the FSDT finite element into delaminated and intact segments and calculated the natural frequencies and mode shapes of delaminated composite plates. Chen et al. [13] considered the progressive failure process of the delamination in a computational model based upon the FSDT laminate theory.

In order to incorporate more accurate cross-sectional warping in First-Order Shear Deformation Theory, Reddy [14] developed a HSDT laminate theory, where displacement expansion through the plate thickness was approximated using the cubic series expansion of thickness coordinates. Başar et al. [15] used these refined shear-deformation models with finite rotations, allowing for a quadratic shear deformation distribution across the thickness. They introduced further constraints to simplify the HSDT model to Mindlin–Reissner type theory and a Kirchhoff–Love type theory. In previous works, Vuksanović [16] investigated single layer models of higher order based on HSDT, and has used HSDT finite elements for the calculation of the dynamic response of intact composite plates. Beside the application to the analysis of laminated composite plates, HSDT finite elements were applied in the analysis of composite sandwich plates, for example in works of Nayak et al. [17,18].

The limitations of ESL theories motivated to derive refined (layerwise) plate theories. These theories consider each layer separately, by assuming the unique displacement field through the thickness of each layer. The Generalized Layerwise Plate Theory (GLPT) proposed by Reddy [19] which was further improved by Barbero and Reddy [20] became the basis for the development of enriched layerwise finite elements, capable to describe the independent motion of every layer separately. Ćetković and Vuksanović have derived both the analytical and numerical (using partial layerwise finite element) solution of the GLPT, for the analysis of intact laminated composite and sandwich plates [5]. Marjanović and Vuksanović [4] have further improved this model to account for delamination kinematics and applied the model for the calculation of natural frequencies, mode shapes and critical buckling loads of delaminated composite and sandwich plates. On the other hand, Alnefaie [21] used a full layerwise finite element model, for calculation of the fundamental dynamic characteristics of laminated plates considering interlaminar damage. Başar et al. [22,23] also developed a family of multi-layer shell elements to calculate the interlaminar stresses with the high accuracy. He used layer-wise shell models to calculate the free vibration response of laminated structures. In order to reduce the computational cost, Botello et al. [24] derived the layerwise finite element model for intact plates using the triangular elements, and presented the substructuring technique to eliminate the in-plane degrees of freedom during the assembly process. Ghoshal et al. [25,26] incorporated interlaminar contact during the "breathing" phenomena in the delaminated zone of smart composite plates. They have used a layered plate model to investigate linear and nonlinear responses of smart composite structures with delamination. Nonlinear contact conditions were incorporated in the analysis of sandwich panels using the high-order sandwich plate theory (HSAPT) [27].

Many authors investigated the delamination in laminated composite and sandwich plates using the shell formulation obtained from a degeneration of 3D solid elements. Klinkel et al. [28] derived a solid element for the nonlinear analysis of laminated shell structures, using natural strain and enhanced assumed strain methods to improve the element behavior. A refined eight-node continuum shell element with enhanced strain, capable to account for delamination using the interface element was presented in work of Sprenger et al. [29]. The shell element with enhanced assumed strains for a geometrically non-linear theory has been presented by Klinkel and Wagner [30]. In their recent study, Dornisch et al. [31] derived an isogeometric Reissner–Mindlin shell element. They described the structure geometry by NURBS surfaces, and accounted for large rotations using geometrically nonlinear formulation.

After the derivation of the fundamental dynamic characteristics of damaged plates, the shell model presented in [4] is further extended in this paper to take into account contact conditions in case of transversal unloading along the interface and transient loading situations. Reddy's Generalized Laminated Plate Theory is used in its extended version. The GLPT assumes independent interpolation of in-plane and out-of-plane displacement components, as well as possible discontinuities along interfaces between adjacent layers. Piece-wise linear variation of in-plane displacement components and constant transverse displacement through the thickness are imposed. It is assumed that C_0-continuity of the displacements through the thickness of the laminate is satisfied. The nodal variables in the finite element model are only translations in three orthogonal directions. Cross-sectional warping is taken into account using the layerwise expansion of the displacements. A consistent mass matrix is employed. The finite shell element based on the GLP Theory developed in this paper is used to perform comparative numerical analyses of the transient response of laminated composite and sandwich plates with and without the presence of embedded delamination and to illustrate how the incorporated geometrical nonlinearity and contact conditions influence the response of damaged laminated composite and sandwich plates.

The paper is organized as follows: Section 2 summarizes the theoretical basis of the proposed shell element. In Section 3, governing equations of the layerwise finite element model based on the proposed theory are derived. Section 4 explains the solution of the resulting time dependent problem using implicit Newmark's integration. In Section 5 a contact algorithm used to prevent the layer overlapping during the "breathing" of the delamination is explained. The verification and applicability of the model using available data from the literature as well as a variety of new benchmark examples for delaminated plates is documented in Section 6. Finally, concluding remarks on the proposed model and its further improvement are provided.

2. Formulation of the theory

2.1. Basic assumptions

In this work we will consider laminated and composite sandwich plates, respectively, composed of n orthotropic layers, as