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Numerical and experimental validation of nonlinear deflection and stress responses of pre-damaged glass-fibre reinforced composite structure

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ABSTRACT

In the present article, nonlinear static deflections of internally damaged shear deformable laminated composite curved (single and doubly) shell panel are investigated numerically under the quasi-static loading and validated with experimental results. For the numerical analysis, a general nonlinear mathematical model of the laminated composite curved shell panel including the effect of the internal damage is derived with the help of two higher-order kinematic theories and Green-Lagrange nonlinear strain. The desired governing equation is obtained by minimizing the energy expression and solved via nonlinear finite element steps. The numerical responses are computed via a generic MATLAB code developed based on the present mathematical formulation. The degree of accuracy of the current numerical model has been checked and the subsequent validation is established by comparing the present results with available published results. In addition, an experimental investigation has also been carried out for the comparison purpose via three-point bend test on the laminated Glass/Epoxy composite with artificial delamination. Lastly, numbers of numerical examples are solved to demonstrate the implicit behavior of the currently developed higher-order nonlinear model for the analysis of the pre-damaged layered structure.

1. Introduction

Since last few decades, the application of layered composites material has been increased rapidly in the manufacturing the weight sensitive and high-performance structures in civil construction, marine, aircraft, aerospace and automobile industries due to their excellent property and ability to be tailored for particular applications (Gay and Hoa, 2007). Most commonly the laminated composite structure does not have any reinforcement in the thickness direction which leads to the high inter-laminar shear stress and subsequent separation of the consecutive layers. The separation of the layer generally termed to be delamination or debonding may arise due to the several reasons and in several ways. Some of the common reasons are entrapment of air pockets or foreign particles, incomplete curing, material and geometric discontinuity during the manufacturing and eccentric and low-velocity impact loading during service life (Sridharan, 2008). The presence of internal debonding could affect the structural integrity and the structural performance significantly. Hence, the thorough understanding and quantitative measurement of the influence of the debonding on the stiffness and structural responses of the laminated structure is very much essential. In order to identify the necessary gaps of the earlier studies on the delaminated structure, a comprehensive review of the previously published literature is discussed in the following lines and subsequent objective of the present article also framed accordingly. The present review is mainly focused on the two major issues i.e., the solution techniques adopted for the desired structural responses and the mid-plane kinematics used for the mathematical modeling purpose of the laminated/delaminated structure.

In the early nineties, the transverse deflection behavior of laminated composite curved shell panels (single and doubly) are investigated numerically by Reddy and Chandrashekhara (1985) using finite element (FE) model based on the extended Sander's shell theory including the von-Karman type of geometrical nonlinear strain-displacement relations. Similarly, FE steps are further utilized to examine the nonlinear bending and the stress behavior of the laminated composites plate by Barbero and Reddy (1990) using the generalized laminated plate theory (GLPT) in

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conjunction with von-Karman nonlinear strain. The FE solutions of the nonlinear static and the transient responses of the laminated composite plate are reported by Chang and Huang (1991) based on the higher-order mid-plane theory and von-Karman geometrical nonlinearity. Also, the nonlinear FE steps are employed to compute the bending strength of the doubly curved laminated composite as well as the sandwich shell panels by Kant and Kommineni (1992, 1994) using the higher-order kinematic theory and von-Karman strains. The nonlinear (static and dynamic) FE solutions of the laminated composites plate are reported by Ganapathi et al. (1996) for the laminated structure using an eight noded quadrilateral element and von-Karman strain-displacement relations. Further, a new plate/shell triangular element is developed by Zhang and Kim (2005) to compute the geometrical nonlinear deflection parameters of the laminated plate based on the first-order mid-plane kinematics. Later, the first-order shear deformation theory (FOST) type of mid-plane kinematics along with von-Karman geometrical nonlinear strains are utilized by Baltacıoglu et al. (2010) for the computation of the flexural strength of the orthotropic laminated structure via numerical methods. The effect of combined pressure and thermal loading on the nonlinear flexural behavior of the laminated composite plate resting on an elastic foundation is analysed by Shen (2000). The closed-form solution of the fundamental frequency and flexural behavior of the sandwich shell panel is presented first time by Biglari and Jafari (2010) with the help of newly developed three-layered higher-order mixed theory. Gupta et al. (2013) reported the FE solutions of the nonlinear flexural responses of the laminated composite plate with growing damage via the FOST kinematics and von-Karman nonlinear strains. Likewise, the static, buckling, flutter and dynamic responses of the functionally graded material (FGM) plate structure using the FE associated non-uniform rational B-spline method by Valizadeh et al. (2013) in the framework of the FOST kinematics. In contrast to the finite element method (FEM), Galerkin Kriging in association with the meshfree approach also employed to compute the buckling and the flexural characteristic of the laminated composite plate by Bui and Nguyen (2013). The nonlinear FE solutions of the large deflection transverse bending characteristics of the FGM sandwich plate is computed using the refined plate theory and von-Karman nonlinearity by Kaci et al. (2013). Further, the four variable refined plate theory is developed first time to investigate the static responses of the FGM plate by Benatta et al. (2014) including the geometrical nonlinearity under the pressure loading. Similarly, the FE technique has been implemented to examine the modal responses of thick and thin laminated structure by Tornabene et al. (2017) in the framework of the equivalent layerwise theory. Unlike the other available techniques, the explicit Dynamic Relaxation method has been employed by Alamatian and Rezaeepazhand. (2016) for the analysis of the nonlinear static characteristic of the laminated composite plate with variable cross-sections. Malta and Martin (Malta et al., 2017) investigated numerically the effect of compressive load on the five-layer flexible pipe using 3D nonlinear FE model.

Now, the articles reviewed in this section for the structure or the structural components with internal damage and solved using various numerical/analytical technique including the large (finite) deformation effect. The influence of the generation and the propagation of the transverse crack on the stiffness behavior of the angle-ply laminated composites plate is reported by Amara et al. (2006). Further, the delaminated composite beam is analysed numerically by Hicks et al. (2003) using the energy method in association with the FE approach and compared with subsequent experimental results. Similarly, the effect of delamination on the laminated tube and bar structures are computed using the simulation model by Carneiro and Savi (Vieira and Savi, 2000). Wang and Shenoi (2003) proposed a new modeling approach based on the linear curved beam theory including the fracture mechanics for the analysis of the delaminated composite curved beam. Likewise, the dynamic characteristics of the laminated composite structure with delamination are modeled using the sub-laminate approach by Manoach et al. (2016). The progressive failure analysis of the damaged layered composite structure with and without stiffener is presented by Riccio et al. (2016, 2017a, 2017b). The system of exact kinematic condition (SEKC) steps have been employed to evaluate the dynamic characteristics by Szekrényes (2015) to study the effect of delamination through the width of the plate to main the kinematic continuity between the laminated and debonded composite. Further, the updated version of SEKC approach is introduced by Szekrényes (2016) to examine the mechanical responses of delaminated composite plates using different mid-plane kinematic (first, second and third-order) plate theories. Similarly, the effect of the location and the length of the delamination are investigated by using new artificial immune system method (Bazardehi et al., 2012; Mohebbi et al., 2013).

The extensive review of the literature reveals that the various work has been attempted and reported on the linear/nonlinear flexural strength of the laminated composite curve and flat panel is mainly using von-Karman type of geometrical nonlinear strains in the framework of FOST and HOST (higher-order shear deformation theory) mid-plane kinematics. In addition, the damaged laminated composite panel model also focused on the edge debonding rather than internal debonding. However, both types of debonding phenomena in the laminate structures are equally important and cannot be avoided. To the best of the authors' knowledge, no FE modeling has been discussed or reported yet in the open literature which accounts the large deformation in Green-Lagrange type of nonlinear strain kinematics in association with HOST mid-plane theory considering the effect of internal damage using the sub-laminate concept. Hence, in the present work authors' aim to develop a generic type of FE model for the laminated curved shell panel with internal damage in the framework of two HOST kinematic model and Green-Lagrange nonlinear strain to evaluate the nonlinear transverse deflection under the quasi-static type of mechanical load. The necessary consistency behavior and the validity of the said higher-order models have been established by solving an adequate number of examples. Further, to show the inevitability of the proposed HOST kinematics the results are compared with experimental results of laminated Glass/Epoxy composite plate with and without damage. Lastly, the importance and effect of the geometrical and material parameters along with various size, position and location of delamination on the nonlinear transverse deflection under two different mechanical load are computed and conferred in details.

2. Theory and formulation

2.1. Geometry of the proposed shell panel

The physical model of the doubly curved laminated composite shell panel (Fig. 1) assumed to be consist of 'N' number of orthotropic layers of

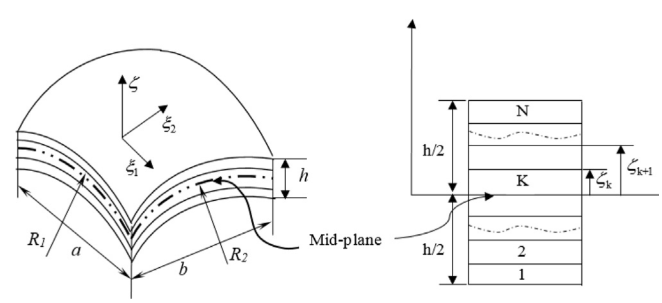

Fig. 1. Geometry of the curved panel.