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Structural analysis of transversally loaded quasi-isotropic rectilinear orthotropic composite circular plates with Galerkin method

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Abstract

Bending analysis of rectilinear orthotropic composite plates have been scarcely investigated taking into account the increasing use of composite materials in structural applications in the last years.

This kind of plates are laminates with axisymmetric geometry and they are made up of unidirectionally reinforced layers with different orientations. Transversally loading this kind of circular plates, the deflected mid-surface is not independent from the circumferential coordinate, unlike the case of isotropic circular plate. Nevertheless, the quasi-isotropic stacking sequence makes still possible to introduce the hypothesis of axisymmetry for the mid-surface deflection under transversal load, disregarding the circumferential variation of the vertical displacement connected to the variable bending stiffness.

Then, the constitutive equations for this specific family of plates were obtained finding the stress resultants-strains relations in the global cylindrical coordinate system. These expressions, along with the equilibrium equations, made it possible to derive the governing equation of the problem in the frame of Kirchhoff-Love hypothesis of the classical lamination theory.

The Galerkin method was applied to solve the governing third order differential equation in terms of mid-surface deflection, introducing appropriate polynomial approximation functions compliant with the boundary conditions. In particular, fully clamped constraint conditions were considered for the outer diameter of the plate in conjunction with an internal rigid core. The characterization of this model allows to define the stiffness matrix terms of a custom composite bolted joint finite element, that is the object of future developments of this work.

Results of the original proposed method are presented and compared to those obtained by means of FEA performed with a refined reference model, demonstrating a good agreement.

Keywords: rectilinear orthotropic composite material; circular plates; bolted connections; Galerkin method;

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1. Introduction

The continuous research of high performances in mechanical design leads to the implementation of composite materials in many industrial sectors. Many are the advantages of composite material choice in typical shell applications, but at the same time a junction of these elements could represent a critical issue. The use of bolted joints is the most common technique when a demountable connection is needed.

The strength and fatigue behavior complete characterization of these joints is an open issue, studied experimentally and numerically for different applications Chowdhury et al. (2016); Giannopoulos et al. (2017); Feo et al. (2017). In aerospace design, anisogrid composite lattice structures are taking the place of metallic shells Belardi et al. (2017). One of the main issues linked to this technology is the connection of its composite endings to metallic flanges through demountable joints.

In many papers, such as Gray and McCarthy (2010); Gray and Mccarthy (2011), the effects of a bolted connection presence is taken into account by considering global aspects and local strength due to the introduction of simplified bolt models. Recently, Zhou et al. (2015) evaluated the damage around the bolt on the composite laminate with an implicit code approach.

A complete characterization in terms of stiffness of the junction, intended as the bolt and the nearby composite sheet portion, hardly can be found in literature. This could represent the basis for the implementation of a specific FE model of the connection in the manner proposed by Vivio (2009). In Vivio (2009) the author presents an innovative FE approach, based on the modeling of the joint through a theoretical reference model, able of accurately simulate the spot joint stiffness with a very low entry of DOFs in the overall model of a multi jointed structure. A new declination of this model to the application on composite and hybrid composite-metal bolted joints requires a preliminary step which concerns the analytical study of the composite bolted joint reference model. This consists of a portion of laminate nearby the connection that can be modeled as an annular plate realized in rectilinear orthotropic material with clamped outer radius and a rigid core connected to the inner one.

The characterization of this model allows to define the stiffness matrix terms of a custom composite bolted joint finite element, that is the object of future developments of this work.

The choice of selecting a circular plate, as a portion of a rectangular laminate with rectilinear orthotropic material properties for each layer, lead to a problem barely analyzed in literature because of the not-axisymmetry of the plate. This aspect introduces a circumferential variation of the composite annular plate bending stiffnesses. This prevents the attainment of closed form solutions, as for the isotropic case, requiring the adoption of numerical methods. In literature, despite the wide and differentiated range of technical applications of rectilinear orthotropic circular laminates, most of the published works are referred to circular orthotropic laminates and many of the available ones concerns sector plates.

As reported inTimoshenko and Woinowsky-Krieger (1959), Lekhnitskii et al. (1968) performed the first study about this topic which concerns elliptic and circular plates, that exhibit rectilinear orthotropic material properties, clamped at the outer radius and undergoing a uniform transversal load. This particular loading condition was solved supposing a specific mid-surface deflection function fulfilling the problem governing equation.

Tang (1972) made use of Galerkin method to discuss the elastic stability of circular composite plates featuring rectilinear anisotropy subject to in-plane compressive forces along the external edge. A buckling mode characterized by axisymmetric deflection of the plate mid-surface is assumed in the solution. Two cases of load application are considered: uniform in-plane compression of the plate mid-surface and unidirectional application of the compression force. Both results show that, because of the initial assumption of rotationally symmetric deflection, the stiffnesses terms due to bending-twisting coupling do not influence the critical buckling load.

In Fu and Waas (1992), the authors analyzed the problem of polar and rectilinear orthotropic annular circular plate undergoing both internal or external pressure loading, without restriction to axisymmetric buckling modes, making use of the Rayleigh-Ritz method. In the polar orthotropic case the pre-stress distributions are exactly evaluated, meanwhile the rectilinear orthotropic pre-buckling stress state is approximated through Galerkin method and introducing the Airy stress function. It is demonstrated that the non-axisymmetric modes of buckling are often the critical ones. Seifi et al. (2012) dealt with symmetric buckling of cross-ply laminated annular thin plates, buckling loads and mode shapes were derived exploiting the energy method and finite element analysis. The effects of thickness, boundary conditions,