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In-plane and out-of-plane vibration modes of laminated composite beams with arbitrary lay-ups

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Abstract
This paper mainly presents the in-plane and out-of-plane vibration analysis of thin-to-moderately thick composite beams with arbitrary lay-ups using the first order shear deformation theory. The material couplings, i.e. bending–stretching, bending–twisting and stretching–twisting couplings, along with the effects of shear deformation, rotary inertia and Poisson's effect are taken into account. In order to obtain the free response of the structure, a semi-analytical solution is adopted based on the variational formulation and solving the weak form of the governing equations by extremizing the objective functional with respect to unknown displacement components and Lagrange multipliers. We also propose a higher order beam element which is a convenient tool for numerical implementation in one-dimensional finite element analysis of the problem. Semi-analytical and finite element solutions are utilized and verified for various numerical case studies. Numerical examples are presented for both the semi-analytical and finite element solutions. The results show excellent agreement with the solutions obtained by the full three-dimensional finite element model in commercial package ANSYS. These numerical examples also demonstrate that ignoring the role of out-of-plane displacement in the conventional one-dimensional models leads to significant error in calculating the torsional modes of laminated composite beams.

Keywords
Laminated Composite Beam; Out-of-plane Vibration; Analytical Solution; Finite Element Solution.

1. Introduction

The ability to design composite structural components with high strength/stiffness to weight ratio and less vulnerability to corrosion/fatigue offers great promise for their diverse functionality. Due to a variety of applications in different environmental conditions and engineering fields (e.g. automobile, aviation and marine industries), composite components are very likely to be subject to loads of complex directions and magnitudes. Accordingly, the accurate and predictive simulation of composite laminates, which are mostly considered as laminated plates and beams, and understanding their dynamic characteristics under different loading conditions are of crucial importance to achieve the desired structural performance.
Fruits of continuous research endeavors in computational mechanics, several theories and analytical/numerical methods have been developed in the literature to understand the free/forced dynamic behaviour of beam-type components, either isotropic or anisotropic [1] [2] [3] [4] [5] [6] [7]. However, in the case of laminated composite beams, it would be surprising to find that the out-of-plane vibrations of members with arbitrary lay-ups have received very little attention among scholars. Herein, the in-plane vibration refers to the beam deformation in the plane which includes the beam lengthwise axis and its thickness (note that the beam thickness is composed of a number of orthotropic layers), while out-of-plane deformation occurs in the plane identified by the beam lengthwise axis and its width. The out-of-plane modal information of laminated beams can play an important role in the practical application of vibration-based structural health monitoring techniques [8] (where the damage detection procedure relies on the change of dynamic characteristics of the system, i.e. natural frequencies, mode shapes, damping,