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A design of laminated composite plates using graded orthotropic fiber-reinforced composite plies

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ABSTRACT

A new lamination scheme is proposed through the design of a graded orthotropic fiber-reinforced composite ply for achieving continuous variations of material properties along the thickness direction of laminated composite plates. First, a micro-structure of graded unidirectional fiber-reinforced composite ply is designed and its effective graded elastic properties are estimated using finite element procedure. Next, the new lamination scheme is demonstrated through the conversion of a conventional laminated composite plate (CLCP) into a conventional-graded laminated composite plate (CGLCP) utilizing presently designed graded orthotropic composite ply. The suitability of this conversion/proposed lamination scheme is substantiated through the bending analysis of both the plates (CLCP and CGLCP).

1. Introduction

Fiber-reinforced composite laminates are widely used in the design of advanced structural components because of their several advantages like high strength-to-weight ratio, high stiffness-to-weight ratio, high fatigue strength, corrosion resistance etc. In spite these advantages, a major drawback of laminated composite structures is the mismatch of material properties at the inter-surface of two adjacent layers. This discrepancy causes delamination of the laminated structures that eventually limits their applications under high mechanical and/or thermal stresses. In order to achieve the continuous variations of material properties and stresses within laminated structures, the concept of functionally graded materials (FGMs) was emerged in an attempt for developing a super heat resistant material [1]. In this proposition of FGM, the metal and ceramic constituents are used to form a lamina in such a manner that the material properties vary smoothly from ceramic to metal or vice versa particularly along the thickness direction. Thus, the discontinuities of material properties along the thickness direction of lamina do not arise even though it (lamina) is made of two different constituent materials. A great deal of research has already been reported on the use of FGMs in the design of various structural components [2–19]. The concept of FGM is also substantially utilized in the design of polymer-matrix based fiber-reinforced composite structures for improving their structural behavior under thermal and/or mechanical loads. Several reports on the design and analysis of fiber-reinforced composite structures having graded material properties along the thickness direction are available in the literature. Aboudi et al. [20] analyzed an FG fiber-reinforced composite plate with varying fiber-spacing along thickness direction and investigated the effect of an applied temperature differential across the thickness of the plate on the internal temperature, stress distributions, force resultants and moment resultants. A similar thermo-elastic analysis for an FG fiber-reinforced composite plate having functionally graded properties in two directions was also carried out by Aboudi and Pindera [21]. Wetherhold et al. [22] introduced an FG symmetric laminated fiber-reinforced composite beam of continuously varying fiber-volume fraction (FVF) along the thickness direction. This study shows the advantage of creating a graded fiber-reinforced composite beam for eliminating or controlling thermal deformations. Aboudi et al. [23] presented optimal distributions of fiber-phase across the thickness of an FG fiber-reinforced composite plate for achieving minimum in-plane moment resultant due to an applied thermal gradient. Pindera and Dunn [24] carried out a finite element analysis of an FG fiber-reinforced plate subjected to a temperature gradient across the thickness of the plate. The finite element results in this study are compared with similar results obtained by using higher-order theory for FG materials [20].

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Benatta et al. [25] considered continuous variation of FVF along the thickness direction of a short fiber-reinforced composite beam and demonstrated the effects of different distributions of FVF on the bending response of the beam. Bedjilili et al. [26] presented free vibration characteristics of a symmetric composite beam with variable FVF along the thickness direction. Han et al. [27] considered sigmoid distributions of FVF across the thickness of composite plates and shells. This study demonstrates the effect of this special type of distribution of FVF on the nonlinear structural behavior of graded plates and shells. Kuo and Shiau [28] presented the effect of variation of FVF along the thickness direction of a laminated composite plate on its critical buckling loads and natural frequencies. Oyekoya et al. [29] developed a finite element model of a composite plate having functionally variable FVF along any of the axes of reference coordinate system. Bouremana et al. [30] performed thermo-elastic analysis of a symmetric laminated composite beam in order to minimize the thermal deformation of the beam by varying its FVF along the thickness direction. Shen [31] and Shen and Zhang [32,33] proposed an FG fiber-reinforced composite laminated plate. Every composite ply in this laminate has constant FVF, but the composite plies within the laminate are of different FVFs. The corresponding structural advantages are presented through large amplitude vibration and post buckling analyses of the laminated composite plate. Tahouneh et al. [34] presented free vibration analysis of a thick annular fiber-reinforced composite plate of variable FVF along the thickness direction. Similar to FVF, the fiber orientation angle within the fiber-reinforced composite lamina is another important parameter for achieving its graded material properties along the thickness direction. Batra and Jin [35] analyzed a graded composite plate with varying fiber orientation angle along the thickness direction and investigated the effect the variation of fiber orientation angle on the resonant frequencies of the plate. Cho and Rowlands [36] presented an optimized local fiber orientation angle near the holes or notches of composite structure in order to reduce associated stress-concentration. Panda and Ray [37] presented the controlled nonlinear transient responses of laminated composite plates of variable fiber orientation angle along the thickness direction. Yas and Aragh [38,39] analyzed the free vibration characteristics of cylindrical panels with continuous variations of FVF and fiber-orientation angle along the radial direction.

The variation of fiber orientation angle in a fiber-reinforced composite lamina yields anisotropic material properties of the lamina. So, for achieving graded orthotropic material properties across the thickness of fiber-reinforced composite lamina, one would follow the variation of FVF in the same (thickness) direction. Present study is concerned with the graded orthotropic fiber-reinforced composites with varying FVF along the thickness direction. The aforesaid analyses of graded orthotropic fiber-reinforced composite laminas/laminates demonstrate their improved structural characteristics for the use of graded material properties along the thickness direction. But, a methodology for achieving continuously varying material properties across the thickness of a laminated fiber-reinforced composite structure with varying FVF is not addressed. Recently, Fu et al. [40] analyzed laminated composite plates comprised of graded orthotropic fiber-reinforced composite plies with varying FVF along the thickness direction. The continuous variations of stresses in this study [40] indicate the variations of material properties in the same (continuous) manner and this is accomplished by mean of low FVF of graded plies at their interlaminar surfaces. Although the reduced interlaminar stress-mismatch or material property-mismatch is attained [40], but the stress-concentration for every in-plane normal stress arises at the top/bottom surface of the laminate. Moreover, the use of graded ply for all layers of laminate and the consideration of low FVF at interlaminar surfaces of plies may significantly affect the rigidity of overall laminate. This issue of the change of laminate-rigidity is not addressed in the same study [40] while achieving reduced interlaminar stress-mismatch. It is well known that laminate-rigidity; maximum values of stresses and stress-concentration are major issues in the design of a laminated composite structure. In order to maintain these features in the design of a composite laminate while achieving the continuous variations of material properties in the thickness direction, presently a new lamination scheme is proposed through the design of a graded orthotropic fiber-reinforced composite lamina with varying FVF across its (lamina) thickness. The proposed strategy of lamination utilizes graded as well as conventional orthotropic composite plies. The graded composite plies work mainly for eliminating the mismatch of material properties at the interlaminar surfaces of plies while the conventional plies strengthen the overall laminate. The new lamination scheme is demonstrated through the conversion of a conventional laminated composite plate (CLCP) into a conventional-graded laminated composite plate (CGLCP). A bending analysis of these plates (CLCP and CGLCP) is carried out for investigating the suitability of present conversion of a CLCP through the corresponding changes in laminate-rigidity, stress-mismatch at interlaminar surfaces, stress-concentration and maximum values of stresses in the laminate.

The graded fiber-reinforced composite ply in the present lamination scheme is considered to be a stack of horizontal layers of unidirectional fiber-reinforced composite. Every layer is comprised of one row of horizontally coplanar continuous fibers embedded within epoxy matrix. The fibers in every layer are aligned in the plane of lamina and oriented uniformly. All fibers within a layer are of identical cross-sectional area. But the same (area) varies layer-wise for achieving the variation of FVF among the layers within the lamina following a simple power-law. Using the finite element (FE) procedure, the volume-average elastic properties of the graded composite ply are first estimated, those are subsequently expressed as effective graded properties using a concept [41,42] of homogeneous layers in functionally graded composite. To the best knowledge of authors, similar design of a graded orthotropic fiber-reinforced composite ply and the proposed lamination scheme for achieving continuous variations of material properties across the thickness of fiber-reinforced composite laminate are not yet available in the literature.

2. Present graded composite lamina

Fig. 1(a) shows a unidirectional continuous fiber-reinforced composite lamina. The fibers within the lamina are oriented in parallel to x axis and a typical cross-section of the lamina in yz-plane is illustrated in Fig. 1(b). The thickness of the lamina is denoted by, h. The basic building block of this composite is a fiber-matrix pack that is in shape of a rectangular parallelepiped. A fiber-matrix pack is comprised of a continuous fiber embedded within the epoxy matrix and its longitudinal, lateral and transverse directions are in parallel to x, y and z axes, respectively. The axes of a fiber-matrix pack and its fiber lie on the same line in parallel to x axis while the cross-sections of both are considered in shape of square section. The fiber is supposed to be perfectly bonded with the matrix-phase and the linear elastic materials for both the phases are assumed. The side of the square cross-section of a fiber is denoted by a_f and that of the corresponding fiber-matrix pack is denoted by, a_c. The volume fractions of fiber and matrix phases within a fiber-matrix pack are designated by the symbols, v_f and v_m, respectively. A group of fiber-matrix packs having horizontally coplanar axes is designated as a layer of fiber-matrix packs and it (layer) is denoted by, k^{th}-layer (Fig. 1(b)). Also, the axes of any two vertically consecutive fibers/fiber-matrix packs lie on the same