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Buckling analysis of three dimensional braided composite plates under uniaxial loading using Inverse Hyperbolic Shear Deformation Theory

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ABSTRACT

Three dimensional braided composites exhibit several distinct advantages which are not realised in traditional laminates. This is due to the out of plane orientation of some fibers & fully integrated nature of fiber arrangements of three dimensional braided composites that enhance stiffness/strength in the thickness direction and eliminate the inter-laminar surface characteristics. A recently developed Inverse Hyperbolic Shear Deformation Theory (IHSDT) has proved its accuracy and efficiency for static and buckling analysis of laminated composite and sandwich structures. However, its efficacy for the three dimensional braided composites has not examined so far in the literature. In present study, applicability and efficacy of IHSDT has been analysed for the buckling analysis of three dimensional braided composite plates. The effects of various parameters of three dimensional braided composite on the buckling response are examined in details. It is observed that the geometric parameter (aspect ratio), fiber volume fraction and braiding angle have a significant effect on the buckling response of the braided composite plates. It is also observed from the results that the IHSDT accurately predicts the buckling responses of the braided composite plates.

1. Introduction

Composite reinforced with three-dimensional (3D) preform has various unique advantages which are not realized in traditional laminates. Due to the orientation of some fibers in thickness direction, three-dimensional braided composites exhibit enhanced stiffness and strength in the thickness direction. The fully continuous fiber arrangement in three-dimensional preform eliminates the inter-laminar surface characteristic of the laminated composites and exhibits the superior damage tolerance and fracture resistance in impact loading. Textile composite can provide near net shape design of the braided composite components and hence minimizes the need for cutting and joining the parts; thus reduces the overall manufacturing cost. There are huge challenges and opportunities in the three-dimensional braided composite structures.

The development of advanced 3D braided composites for specialised aircraft components began in the late 1960s, and these materials have increasing attention due to their potential uses in aircraft, marine vessels, civil infrastructure and medical application. The potential uses of composites made with 3D woven or 3D braided fabrics range from I-beams, T-joints, rocket motor nozzles and rib-stiffened panels have increased over the year. Stitching has excellent potential for joining composites and thus improves the damage tolerance of structures. Despite the wide variety of demonstration components made from 3D textile composites, these materials currently have few commercial applications. The reason for the low usage of 3D woven, braided, stitched and knitted composites is due to a combination of economic, manufacturing, mechanical property and durability issues. The 2D textile fabrics are extensively used in the composites industry but the advanced three dimensional textile production techniques are new to most designers and manufacturers of composite structures.

Xiao et al. [1] predicted the strength of triaxially braided composites by finite element model by taking consideration of Representative Unit Cell. Wei et al. [2] proposed a new method for calculating the tensile strength of the 3D braided composites. Shokrieh and Mazloomi [3] developed a new analytical model for calculation of stiffness of three-dimensional four-directional braided composites. Li et al. [4] used the unit cell model to predict the stiffness and strength properties of 3D five-directional braided composites by a micromechanical method. Hassan et al. [5] investigated the comprehensive micromechanics of 3D periodic composite structure reinforced with a grid of orthotropic reinforcements. Fan et al. [6] developed a new scheme and microstructural model

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for 3D full 5-directional braided composites. Chen et al. [7] studied the microstructure of 3D braided preforms produced by the four-step 1×1 method. Zuorong et al. [8] evaluated the elastic properties of 3D (4-step) rectangular braided composites by a homogenisation method. Li et al. [9] proposed a new parameterized 3D meso-mechanical based on the microstructure of 3D five-directional rectangular braided composites that enabled the prediction of meso-scale mechanical response and elastic properties in a fast, accurate and effective manner.

Zeng et al. [10] developed a method to predict the effective moduli and the local stress within 3D braided composites under the 3D mechanical loading. Zhang et al. [11] investigated the mechanical behaviour of the 3D four-step braided composite based on three unit-cells model by finite element analysis and the effects of braiding angle and fiber volume fraction on the effective elastic constants of 3D braided composites are also investigated in detail. Chen et al. [12] proposed a Finite Multiphase Element Method to analyse the effective elastic properties of 3-D braided composites and the use of multiphase element leads to a simplified finite element discretisation procedure. Potluri and Manan [13] focuses on mechanics of geometric and micromechanical modelling of non-orthogonal textile composite structures. Tsai et al. [14] proposed a parallelogram spring model to investigate the effects of fabric parameters (such as braid angle, fiber volume fraction and the aspect ratio) on the elastic moduli of braided composite plates.

Sun et al. [15] presented a novel modelling approach for designing and constructing CAD-based composite unit cells. Wang and Wang [16] presented an analysis method which describes the yarn structures in 3D braided preforms. Chen and Li [17] suggested a new micro-macro-mechanical model and analysed the dynamic response of 3D-braided rectangular plates on an elastic foundation. Mouritz et al. [18] reviewed the current and future potential applications for advanced three-dimensional fiber textile composites of weaving, braiding, stitching and knitting.

Miravete et al. [19] proposed a new analytical meso-mechanical approach for 3D braided composite materials and a failure criterion taking into account yarn and matrix degradation to predict failure theoretically. Bianchi et al. [20] presented a finite element model to analyse the structural deformation, strength properties and delamination fracture behaviour of composite T-joints reinforced with z-pins. Barbero et al. [21] developed a novel procedure for finite level discretisation of the yarn and matrix geometry in single lamina and laminated fabric reinforced composites and meso-scale damage model for predicting the in-elastic behaviour of woven fabric composite using ANSYS. Zako et al. [22] proposed three-dimensional finite element analysis based on damage mechanics for investigating the damage mechanisms of woven fabric composite materials. Goyal and Whitcomb [23] analysed the effect of fiber properties on plastic behaviour of 2×2 biaxial braided. Lomov et al. [24] used full-field strain measurements for validation of meso-FE analysis of textile composites. Yao et al. [25] studied the static and bending fatigue properties of ultra-thick 3D orthogonal woven composites and analysed the failure mechanisms and fracture modes.

Li and Shen [26,27] investigated the postbuckling behaviour of 3D braided composite cylindrical shells under torsion and axial compression in thermal environments. The governing equations are based on a higher-order shear deformation shell theory with a von Karman–Donnell-type of kinematic nonlinearity and including thermal effects. Hu et al. [28] analysed the effects of bridging in a 3D composite on buckling, postbuckling and growth of delamination. Li [29] investigated the thermal postbuckling behaviour of 3D Braided Rectangular plates, based on Reddy's higher-order shear deformation plate theory. Li [30,31] analysed the postbuckling behaviour of 3D Braided Rectangular plates subjected to uniaxial and biaxial compression.

Grover et al. [32] developed new ESL theory which is referred as Inverse Hyperbolic Shear Deformation Theory (IHSDT) used for static and buckling response of laminated composites and sandwich plates and it has been observed that IHSDT predicts excellent results for laminated and sandwich plates compared to other theories and 3D elasticity results. Refs. [26–31] used first order and Reddy's third order shear deformation theory for static and buckling response of three dimensional braided composite.

In this study the IHSDT has been applied for the buckling response of three dimensional braided composite. Finite element solution is obtained for the buckling analysis of three dimensional braided composite plates. The von-Karman type nonlinearity has been accounted for evaluation of geometric stiffness. A detailed parametric study (aspect ratio, fiber volume fraction and braiding angle) of the braided composite plate has been conducted in the study.

2. Mathematical formulation

2.1. Displacement field

A rectangular plate of dimension (a × b × h) is considered in the Cartesian coordinate system (X-Y-Z), as shown in Fig. 1. The non-polynomial IHSDT displacement field developed by Grover et al. [32] for 2D laminated composite plate is now proposed for the three dimensional braided composite plates and the field is given as below.

$$\begin{aligned} u(x,y,z) &= u_0(x,y) - z\frac{\partial w}{\partial x} + \left\{\sinh^{-1}\left(\frac{rz}{h}\right) - z\frac{2r}{h\sqrt{r^2+4}}\right\}\theta_x \\ v(x,y,z) &= v_0(x,y) - z\frac{\partial w}{\partial y} + \left\{\sinh^{-1}\left(\frac{rz}{h}\right) - z\frac{2r}{h\sqrt{r^2+4}}\right\}\theta_y \\ w &= w_0(x,y) \end{aligned} \tag{1}$$

where u_0, v_0, w_0 are the middle plane displacements and θ_x *and* θ_y are the shear deformation at the mid plane. The h is the overall thickness of plate and the parameter r is the transverse shear stress parameter and in present case r is taken as 3 [32].

The Eq. (1) is rewritten as:

$$\begin{aligned} u(x,y,z) &= u_0(x,y) - z\phi_x + f(z)\theta_x \\ v(x,y,z) &= v_0(x,y) - z\phi_y + f(z)\theta_y \\ w &= w_0(x,y) \end{aligned} \tag{2}$$

where,

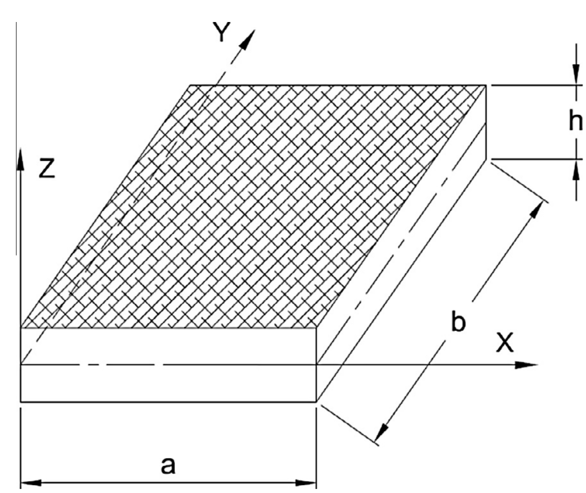

Fig. 1. Braided composite plate in Cartesian coordinates.