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Environmental effects on the free vibration of curvilinear fibre composite laminates with cutouts

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ABSTRACT

In this paper, we study the free vibration characteristics of curvilinear fibre composite laminates exposed to hygrothermal environment. The formulation is based on the transverse shear deformation theory and it accounts for the lamina material properties at elevated moisture concentrations and thermal gradients. A 4-noded shear flexible quadrilateral plate element based on extended finite element approach is employed for the spatial discretization. The effect of a centrally located cut-out, modelled within the framework of the extended finite element method, is also studied. A detailed parametric investigation by varying the curvilinear fibre angles at the centre and at the edge of the laminate, the plate geometry, the geometry of the cut-out, the moisture concentration, the thermal gradient and the boundary conditions on the vibration characteristics is numerically studied and it is hoped that this detailed study will help the designers in optimizing such structures under dynamic situation.

1. Introduction

In the conventional fibre laminated composites, the orientation of the fibres within a lamina is constant. In this type of construction, the stiffness of the laminate does not vary in the domain and are coined as constant stiffness laminates (CSCL). Composite materials with varying stiffness has received greater interest, as they may lead to better and efficient design [1–4]. The stiffness of the composite material can be varied by: (a) using curvilinear fibres; (b) varying the volume fraction or varying the fibre spacing; (c) dropping or adding plies to the laminate and (d) attaching discrete stiffeners to the laminates. In the nineties, Hyer and Lee [1] introduced the concept of variable stiffness panels to improve the structural response of panels with holes. Although, the concept of tailored composite was developed two decades back, recently understanding the response of VSCL has gained increasing attention [5–10]. This can be attributed to the advances in manufacturing capability. Kim et al. [11–13], have demonstrated a process to manufacture variable angle composites. When composite laminates are modelled as plate structures, with VSCL, the plate stiffness coefficients vary with spatial coordinates. Such laminates not only have variable in-plane stiffness, in general may possess variable bending and coupling stiffness. In practice, the structures can experience multiple load scenarios and load paths. Potential advantage of laminates with curved fibres is that VSCL panels offer possibility to alter loading paths. To this end, generating a realistic fibre angle distributions becomes an optimization problem. By using the information of lamination parameters combined with satisfying the constraint on in-plane fibre angle curvature, optimal fibre angle distributions for VSCL have been proposed in Refs. [2,4,14]. A full three dimensional finite element simulation was performed in Ref. [13] to model the VSCL as manufactured and study the first ply failure and matrix cracking. Abdalla et al. [5], studied thermo-mechanical response of VSCL panels. Akhavan and Ribeiro [6] and Akhavan et al. [9,10], studied the static and dynamic response of laminated plates with curvilinear fibres by employing the third order shear deformation theory. Their study demonstrated that the mode shapes of VSCL plates are different from the CSCL. However, the influence of curvilinear fibres was more significant in thin plates. Rouhi et al. [15], used a multi-objective design optimization method to find the optimum fibre angle

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distributions for VSCL cylinders. By adopting the classical laminated plate theory and Ritz procedure, Honda and Narita [16] studied the natural frequencies of laminates with curvilinear paths.

It is evident from the literature that understanding the response of VSCL panels has received considerable attention and studies were made employing the classical lamination theory, first order theory or third order shear deformation theory to describe the plate kinematics, and the method of solution is based on either analytical approach or conventional finite element method. It is also revealed from the literature that the most of the available work use the randomly chosen fibre angles at the centre and at the edge of the laminates and a detailed parametric investigation by varying these angles and their influence on the structural response seems to be scarce in the literature. Also, to the author's knowledge, the influence of temperature and moisture concentration has not been included in the formulation when studying the response of variable stiffness composites.

The moisture concentration and the thermal environment can have significant impact on the response of such laminated structures [17,18]. The change in the temperature and moisture concentration, degrades the elastic moduli and the strength of the composite. This leads to development of hygrothermal stresses within the laminate which influences the response. Moreover a presence of a geometric discontinuity, such as, a cutout can significantly influence the fundamental frequency. Hence it is important to study the response of VSCL structures with a cutout and in the presence of moisture and temperature. Hygrothermal effects on constant stiffness laminates have been studied in detail in the literature [19–23,18]. Whitney and Ashton [19] employed Ritz method to analyze the effect of environment on the free vibration of symmetric laminates. Ram and Sinha [20] employed finite element technique to study the influence of temperature and moisture on the bending characteristics of laminated plates. Patel et al. [22], employed shear flexible Q8 quadrilateral element to study the hygrothermal effects on the structural behaviour of thick composite laminates. Patel et al., employed higher order accurate theory and studied the importance of retaining higher order terms in the displacement approximation. Lo et al. [23], employed a four-node quadrilateral element based on the global-local higher order theory to study the response of laminated plates in the presence of hygrothermal environment. The influence of hygrothermal environment on the angle-ply laminated plates was studied in Ref. [18] by employing a sinusoidal shear deformation theory. The study concluded that hygrothermal environment has significant influence on the global response of laminated plates.

1.1. *Objective*

In this study, we study the influence of moisture and temperature on the fundamental frequency of laminated plates with curvilinear fibres. The influence of a centrally located cutouts is also studied. The cutout is modelled independent of the underlying mesh by employing the extended finite element method (XFEM). The plate kinematics is based on the first order shear deformation theory and a 4-noded shear flexible quadrilateral plate element is employed for spatial discretization. A systematic parametric study is carried out to bring the effect of the boundary conditions, the thermal gradient ΔT, the change in moisture concentration ΔC and the plate geometry on the free flexural vibration of laminated composites.

1.2. *Outline*

The paper is organized as follows, the next section will give a brief overview of Reissner-Mindlin plate theory. Section 3 illustrates the spatial discretization and the basic idea of XFEM as applicable to plates to represent the internal discontinuous surface, viz., cutouts in this study. Section 4 presents a systematic parametric study to bring out the influence of various parameters, followed by concluding remarks in the last section.

2. Theoretical formulation

Using the Mindlin formulation, the displacements u,v,w at a point (x,y,z) in the plate (see Fig. 1) from the median surface are expressed as functions of the mid-plane displacements u_o,v_o,w_o and independent rotations β_x,β_y of the normal in yz and xz planes, respectively, as

$$\begin{aligned} u(x,y,z,t) &= u_o(x,y,t) + z\beta_x(x,y,t) \\ v(x,y,z,t) &= v_o(x,y,t) + z\beta_y(x,y,t) \\ w(x,y,z,t) &= w_o(x,y,t) \end{aligned} \quad (1)$$

where t is the time. The strains in terms of mid-plane deformation can be written as:

$$\boldsymbol{\varepsilon} = \begin{Bmatrix} \boldsymbol{\varepsilon}_p \\ \mathbf{0} \end{Bmatrix} + \begin{Bmatrix} z\boldsymbol{\varepsilon}_b \\ \boldsymbol{\varepsilon}_s \end{Bmatrix} - \{\bar{\boldsymbol{\varepsilon}}_o\} \quad (2)$$

The midplane strains $\boldsymbol{\varepsilon}_p$, the bending strains $\boldsymbol{\varepsilon}_b$ and the shear strains ε_s in Equation (2) are written as:

$$\boldsymbol{\varepsilon}_p = \begin{Bmatrix} u_{o,x} \\ v_{o,y} \\ u_{o,y} + v_{o,x} \end{Bmatrix}, \quad \boldsymbol{\varepsilon}_b = \begin{Bmatrix} \beta_{x,x} \\ \beta_{y,y} \\ \beta_{x,y} + \beta_{y,x} \end{Bmatrix}, \quad \boldsymbol{\varepsilon}_s = \begin{Bmatrix} \beta_x + w_{o,x} \\ \beta_y + w_{o,y} \end{Bmatrix}. \quad (3)$$

where the subscript ‘comma’ represents the partial derivative with respect to the spatial coordinate succeeding it. The strain vector $\{\bar{\varepsilon}_o\}$ due to temperature and moisture is represented as:

$$\bar{\boldsymbol{\varepsilon}}_o = \begin{Bmatrix} \bar{\varepsilon}_{xx} \\ \bar{\varepsilon}_{yy} \\ \bar{\varepsilon}_{xy} \end{Bmatrix} = \Delta T \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy} \end{Bmatrix} + \Delta C \begin{Bmatrix} \gamma_x \\ \gamma_y \\ \gamma_{xy} \end{Bmatrix} \quad (4)$$

where ΔT and ΔC are the rise in temperature and the moisture concentration, respectively. α_x,α_y and α_{xy} are the thermal expansion coefficients in the plate coordinates and can be related to the thermal coefficients (α_1,α_2 and α_3) in the material principal directions and γ_x,γ_y and γ_{xy} are the moisture expansion coefficients similar to thermal expansion coefficients in the plate coordinates. The constitutive relations for an arbitrary layer k in the laminate (x,y,z) coordinate system can be expressed as:

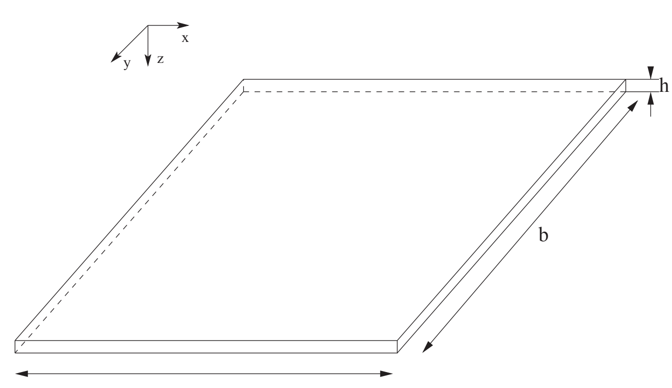

Fig. 1. Coordinate system of a rectangular laminated plate.