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Assessment of certain higher-order structural models based on global approach for bending analysis of curvilinear composite laminates

Anand Venkatachari [a,c], S. Natarajan [b,*], K. Ramajeyathilagam [c], M. Ganapathi [a]

[a] Tech Manhindra Ltd., Electronic City, Bangalore 560100, India
[b] Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India.
[c] School of Aeronautical Sciences, Hindustan University, Keelambakkam, Chennai 603103, India

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ABSTRACT

In this paper, the performance of different structural models based on global approach in evaluating the static response of curvilinear fibre composite laminates is analyzed. A C^o shear flexible Quad-8 element developed based on higher-order structural theory is employed for the present study. The structural theory accounting for the realistic variation of displacements through the thickness and the possible discontinuity in the slope at the interface is considered. Four alternate discrete structural models, deduced from the generic structural model by retaining various terms in the displacement functions are examined for their applicability. The accuracy of the present formulation is demonstrated considering the problems for which analytical solutions are available. A systematic numerical study, assuming different ply-angle and lay-up, is conducted in bringing out the influence of various structural models on the static response of composite laminates with curvilinear fibres.

1. Introduction

The need for high strength-to and high stiffness-to-weight ratio materials has led to the development of laminated composite materials. This class of material has seen increasing utilization as structural elements and as primary structures of large-scale aerospace structures [1]. This is because of the possibility to tailor the properties to optimize the structural response. Conventionally, the fibre reinforced composites have straight and unidirectional fibres. In this type of construction, the stiffness of the laminate does not vary in the domain. However, recently, the composite materials with varying stiffness has received greater interest, as they may lead to better and efficient design [2–5]. The stiffness of the composite material can be varied by: (a) using curvilinear fibres [2]; (b) varying the volume fraction or varying the fibre spacing [6]; (c) dropping or adding plies to the laminate [7] and (d) attaching discrete stiffeners to the laminates [8]. Among these concepts related to variable stiffness composite laminates (VSCL), the approach of curvilinear fibre does not introduce major geometry variations, it however does impose the constraint on the curvature of the fibre. In the following, we restrict ourselves to work related to composite laminates with curvilinear fibres. Laminates with curvilinear fibres offers a wider degree of possibilities than variations of rectilinear fibre volume fraction and provides a solution to the problem of continuity when manufacturing a structure with different fibre angles in adjoining element. Furthermore, it exhibits a way to diminish the stress concentration in cutouts. Hyer and Lee [2] introduced the concept of variable stiffness panels to improve the structural response of panels with holes. Gürdal and Olmedo [9] studied the in-plane response of VSCL. Although the concept of tailored fibre orientation was developed in the nineties, the design based on VSCL has recently spurred interest among researchers [10–16] due to the improvement in the manufacturing capability [17,18]. Kim et al., [17,18] have demonstrated a process to manufacture variable angle composites. A numerical analysis tool has been developed, using 3D finite elements domain, to simulate the first-ply failure of tow-steered panels under tensile load [19]. When composite laminates are modeled 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.

Abdalla et al., [10] by employing the classical lamination theory and the generalized reciprocal approximation, maximized the fundamental frequency of composite laminates. Their study showed that by employing VSCL significant increase in the fundamental frequency is achieved when compared to constant stiffness panels. This was later extended to study nonlinear dynamic response of VSCL. By using the $p-$version finite element, Akhavan and Ribeiro

* Corresponding author. Tel.: +91 44 2257 4650.
E-mail addresses: snatarajan@cardiffalumni.org.uk, sundararajan.natarajan@gmail.com (S. Natarajan).

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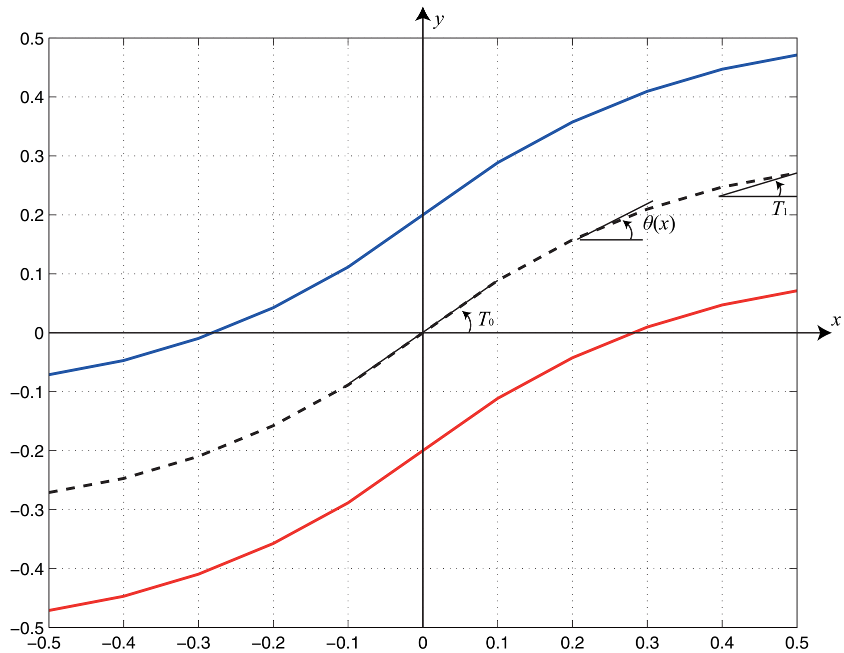

Fig. 1. Reference fibre path ('dashed line') and the shifted fibres ('solid line') for a laminae.

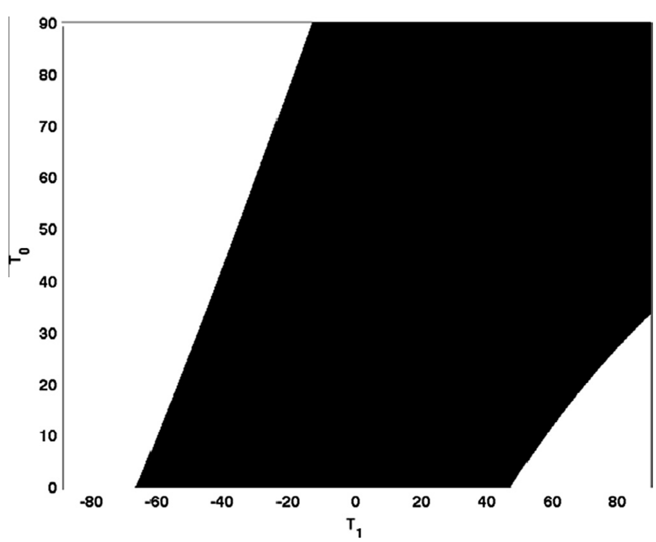

Fig. 2. Curvilinear fibre composite laminate: design space. The 'dark' shaded region depicts the fibre path that satisfies the curvature constraint. The values of fibre orientation, T_o and T_1 are in degrees.

[11] studied the fundamental frequencies and mode shapes of laminated composites with curvilinear fibres. It was inferred that VSCL introduces greater degree of flexibility in adjusting the frequencies and mode shapes. Honda and Narita [12,20], studied the fundamental frequency of VSCL by employing classical plate theory. It was shown that the mode shapes of VSCL are significantly different from the constant stiffness laminated composites. Houmat [13] investigated the nonlinear free vibration of laminated rectangular plates with curvilinear fibres. Groh and Weaver [14] and Raju et al., [15,21] studied buckling of variable thickness curvilinear fibre panel using differential quadrature method. It was inferred that for VSCL shell-like description more accurately characterizes the buckling phenomenon than a plate-like description. A 2D analytical model based on equivalent single-layer formulation introduced recently in [22] in predicting the static response of curvilinear fibre laminates and the governing equations were solved by employing the differential quadrature method. Akhavan et al., [16,23] employed the $p-$version finite element and studied the response of laminated composites with curvilinear fibres under static and dynamic loads. The plate kinematics was represented by third-order shear deformation theory.

It is evident from the literature that the dynamic response of VSCL has received greater attention, whilst, the studies on the static characteristics of VSCL structural elements are limited. The existing studies employed either classical lamination theory, first order or the third order shear deformation theory. However, these theories have limitation when employed to study the response of curvilinear fibre laminated composites. More accurate analytical/numerical models based on the three-dimensional models can be computationally involved and expensive. A layer wise theory is a possible candidature for this purpose, but it may be computationally expensive as the number of unknowns to be solved increases with increasing number of mathematical or physical layers. Hence, among the researchers, there is a growing appreciation of the importance of applying two-dimensional theories with new kinematics for accurate analysis. It is observed from the literature [24–26] that, for realistic structural analysis of laminated composites, higher-order theory with the inclusion of zig-zag function is necessary. The zig-zag function incorporated in the in-plane kinematics has been employed in [24–27] to study laminated composites. Makhecha et al., [26] used higher-order accurate theory based on global approach for multilayered laminated composites by incorporating the realistic through the thickness approximations of the in-plane and transverse displacements by adding a zig-zag function and higher-order terms, respectively. A 8-noded quadrilateral element with 13 degrees of freedom per node was employed for the study. Recently, some researchers have attempted to combine the single layer and discrete layer theories to overcome the limitations of each one. Carrera [28] derived a series of axiomatic approaches for the general description of two-dimensional formulations for multilayered plates and shells. The formulation is a valuable tool for gaining a deep insight into the complex mechanics of laminated structures. In the same spirit, the main objective of this paper is to study the static response of