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Higher-order structural theories for the static analysis of doubly-curved laminated composite panels reinforced by curvilinear fibers

Francesco Tornabene [*,1], Nicholas Fantuzzi, Michele Bacciocchi

DICAM – Department, School of Engineering and Architecture, University of Bologna, Italy

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ABSTRACT

The main aim of this paper is the evaluation of the through-the-thickness profiles of strain, stress and displacement components of several doubly-curved panels reinforced by curvilinear fibers. The placement of the reinforcing phase along curved paths allows to obtain mechanical properties which change point by point and affects the static behavior of shell structures. Some numerical applications based on both higher-order Equivalent Single Layer (ESL) and Layer-Wise (LW) theories are shown in order to underline the curvilinear fiber influence on the static analysis. The structural model, which is based on the so-called Carrera Unified Formulation (CUF), is completely general and can deal easily with variable stiffness shells. An appropriate recovery procedure based on the three-dimensional elasticity equations in principal curvilinear coordinates is presented to compute strains and stresses. The equation system which governs the static problem under consideration is solved numerically through the Generalized Differential Quadrature (GDQ) method. The same numerical technique is employed to evaluate the geometrical parameters needed for the characterization of the shell reference surface, according to the differential geometry.

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1. Introduction

The need of structures able to give high level performances has led to a more intensive use of advanced materials, such as fiber-reinforced composites, laminates, sandwiches, foams and nanostructures [1]. Thus, the main aim of the researches in this field is the development of new classes of materials which can be employed, for instance, to design stiffer structures with limited weight, increase the safety requirements, improve the dynamic behavior, and reduce delamination phenomena. These advantages are well-known by those researchers who work for combining the excellent properties of new materials with the great performances of shell structures [2–6], employed especially in many engineering fields, such as civil, mechanical, aerospace, and naval ones. Several applications which can be found in literature prove the beneficial effects of laminated composite shells and plates, in terms of both static and dynamic behavior [7–25]. The disadvantages of these heterogeneous structures highlighted by many years of research, like delamination and debonding problems [26–28], represented the starting point for the growth of a new class of composite materials without discontinuities, characterized by a gradual variation of the constituents which form the composite. These materials are named Functionally Graded Materials (FGMs) and are currently the subject matter of many researches and applications, as proven by the huge number of papers related to plates and shells made of FGM layers [29–40]. The natural development of these materials suggested progressively the idea of inserting smart components inside the layers of the laminated composites. This awareness caused the growth of the so-called smart structures, such as the piezo-magneto-thermo-elastic reinforced plates [41,42]. Then, remarkable progresses were accomplished in the nanostructure field. One of the most renowned examples is the increasing use of carbon nanofibers, also known as Carbon Nanotubes. In fact, due to their excellent mechanical properties and great potentialities, Carbon Nanotubes were seen immediately as the perfect candidate to constitute the reinforcing phase of several fibrous composites since their discovery in the nineties [43–47]. On the other hand, the need of particular mechanical properties sparked the idea of producing variable stiffness laminates. In general, laminated composite layers are reinforced by rectilinear and uniformly spaced fibers, so that their mechanical properties are constant within the entire domain. Instead, the placement of the reinforcing fibers along curvilinear paths allowed to obtain variable mechanical properties able to improve the structural response. The technological development which affected the manufacturing processes more than twenty years ago made effectively real the possibility to produce composite structures reinforced by

* Corresponding author.
E-mail address: francesco.tornabene@unibo.it (F. Tornabene).
[1] http://software.dicam.unibo.it/diqumaspab-project.

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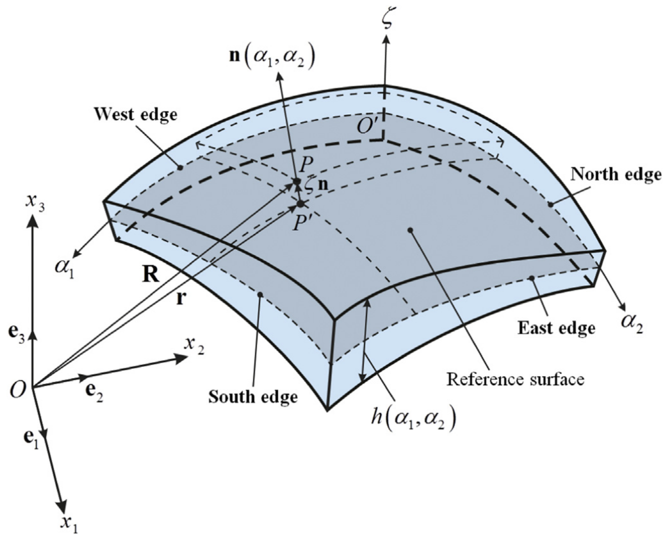

Fig. 1. Doubly-curved panel representation and description.

curvilinear fibers. An accurate description of such composites can be found in Waldhart's thesis [48], in which is illustrated the historical background that led to the improvement of variable stiffness concept. In addition, a complete review about the mechanical behavior of variable stiffness composite laminated structures is carried out in the recent paper by Ribeiro et al. [49]. This review paper highlights that several applications take advantage of the variable stiffness concept mainly to improve the buckling behavior [50–55] and affect the natural frequencies of plates and shells [56–61]. Recently, the forced periodic oscillations of laminates with curved fibers are studied too [62,63]. As concerns the static counterpart, the number of works which can be found in literature is substantially lower, according to the authors' knowledge. In particular, they deal mostly with the computation of deflections of composite plates with curvilinear fibers and the evaluation of stresses between the layer interfaces of laminated structures with variable mechanical properties [64–68]. As it can be noticed from the references specified above, the work that can be done about laminated composite doubly-curved shells is still much. In fact, most of the papers are related to the static and dynamic analyses of laminated plates, whereas only few documents deal with singly-curved shells. The current manuscript arises just from this statement and intends to cover this lack by studying the static behavior of laminated composite doubly-curved panels reinforced by curvilinear fibers. When a shell structure with variable mechanical and geometrical properties is considered, the classic structural models, as the well-known Reissner–Mindlin theory, could not represent properly its mechanical behavior. Therefore, the recourse to more refined structural models is essential to capture the real behavior of a laminated composite doubly-curved structures made of innovative materials. The basis for the development of such higher-order theories can be found in the works by Carrera [69–71] where the author presented the so-called Carrera Unified Formulation (CUF), which is able to describe several kinematic models for plates and shells. Finally, the governing equations of the static problem under consideration are solved numerically through the Generalized Differential Quadrature (GDQ) method, presented by Shu in the nineties [72] as an advanced version of the differential quadrature technique. A general formulation for the GDQ method and its main characteristics are illustrated in depth in the recent review paper [73]. In addition, many examples of accuracy, stability and reliability features of the technique in hand can be found in the works [74–86]. At the end of this introduction, it is convenient to outline the framework of the present manuscript. First of all, a brief synopsis of those differential geometry elements needed to represent a generic doubly-curved surface is presented. Secondly, the shell mechanical behavior is represented by using a general formulation. For this aim, two different methods are introduced and compared. In particular, an Equivalent Single Layer (ESL) model is presented in the first subsection, whereas the consecutive paragraph shows the basis of a Layer-Wise (LW) approach. In addition, a complete exposition for the characterization of the curvilinear fiber paths is illustrated. Finally, some numerical applications for the static analysis based on the GDQ technique are shown to underline the influence of the mechanical property variability on the through-the-thickness profile of strain, stress and displacement components. All these quantities are evaluated numerically by an appropriate recovery procedure based on the three-dimensional elasticity equations in principal curvilinear coordinates.

2. Theoretical model

2.1. Shell geometry description

The mechanical behavior of a moderately thick shell can be studied by considering its reference surface (or middle surface), in which the local reference system $O'\alpha_1\alpha_2\zeta$ is defined (Fig. 1). It should be specified that α_1, α_2 identify the co-ordinates upon the middle surface, whereas the parameter ζ is taken along the shell

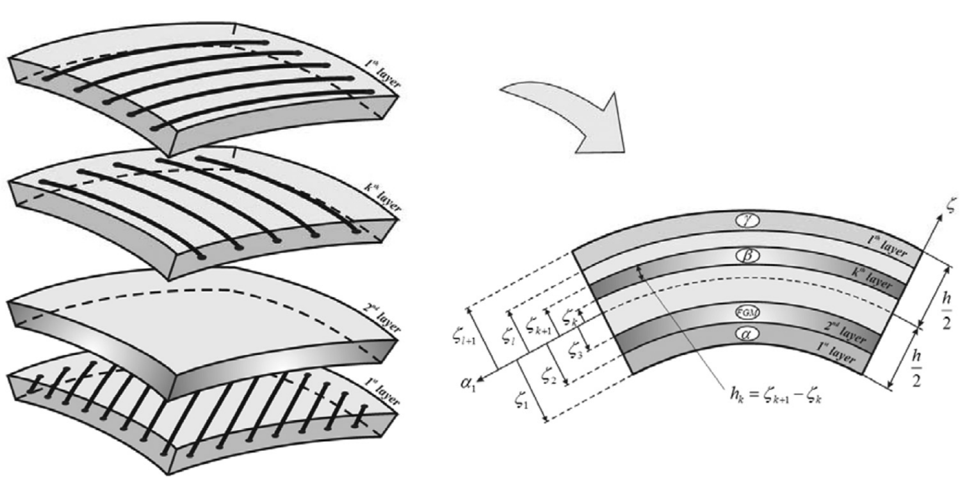

Fig. 2. Coordinate system, layer numbering and orientation used for a laminated shell.

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