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Component-wise analysis of laminated anisotropic composites

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ABSTRACT

This paper proposes a one-dimensional (1D) refined formulation for the analysis of laminated composites which can model single fibers and related matrices, layers and multilayers. Models built by means of an arbitrary combination of these four components lead to a *component-wise* analysis. Different scales can be used in different portions of the structure and this leads to a *global–local* approach. In this work, computational models were developed in the framework of finite element approximations. The 1D FE formulation used has hierarchical features, that is, 3D stress/strain fields can be detected by increasing the order of the 1D model used. The Carrera Unified Formulation (CUF) was exploited to obtain advanced displacement-based theories where the order of the unknown variables over the cross-section is a free parameter of the formulation. Taylor- and Lagrange-type polynomials were used to interpolate the displacement field over the element cross-section. Lagrange polynomials permitted the use of only pure displacements as unknown variables. The related finite element led straightforwardly to the assembly of the stiffness matrices at the structural element interfaces (matrix-to-fiber, matrix-to-layer, layer-to-layer etc). Preliminary assessments with solid model results are proposed in this paper; various numerical examples were carried out on cross-ply symmetrical fiber-reinforced laminates [0/90/0] and a more complex composite C-shaped model. The examples show that the proposed models can analyze laminated structures by combining fibers, matrices, layers and multilayers and by referring to a unique structural finite element formulation.

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1. Introduction

The use of composite materials for aerospace applications is greatly advantageous since composites have better specific properties than traditional metallic materials. A composite structure, for instance, can be some ten times stiffer and two times lighter than an aluminium one. This is the main reason leading to the design of 'full composite' structures for the most advanced aerospace vehicles. Despite this, there are still many key problems to be considered for a more rational use of composite materials such as fatigue and the characterization of failure mechanisms. A better understanding of these key problems in composite structure applications demands enhanced analysis capabilities in various fields. Among these, the present work proposes enhanced structural capabilities to detect accurate stress/strain fields in the matrix, fibers, layers and interfaces of composite layered structures with low computational costs.

Many techniques are available to compute accurate stress/strain fields in the various components of a laminated structure (i.e. fibers, matrices and layers); these techniques are briefly discussed hereafter. The natural manner of refining the analysis of 1D and 2D components consists of using 3D solid finite elements. These elements can be employed to discretize single components (fibers and matrices) or to directly model the layer of a laminated structure; fibers and matrices can be modeled as independent elements or they can be homogenized to compute layer properties. Due to the limitations on the aspect ratio of 3D elements and to the high number of layers used in real applications, computational costs of a solid model can be prohibitive.

Classical theories which are known for traditional beam (1D) and plate/shell (2D) structures have been improved for application to laminates. There are many contributions based on different approaches: higher-order models (Kant and Manjunath, 1989; Kapania and Raciti, 1989), zig–zag theories (Lekhnitskii, 1935; Ambartsumian, 1962; Reissner, 1984; Carrera, 2003) and layer-wise (LW) approaches (Robbins and Reddy, 1993; Carrera, 1998; Carrera and Petrolo, 2012b). So-called *global–local* approaches have also been developed by exploiting the superposition of Equivalent Single Layer models (ESL) and LW (Mourad et al., 2008), or by using the Arlequin method to combine higher- and lower-order theories (Ben Dhia and Rateau, 2005; Biscani et al., 2011).

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Many studies on multiscale problems in composites have recently been conducted as in Mergheim (2009); one of the most important results is that "processes that occur at a certain scale govern the behavior of the system across several (usually larger) scales" (Lu and Kaxiras, 2005). This result implies that the development of analysis capabilities involving many scale levels is necessary in order to properly understand multi-scale phenomena in composites. Various spatial and temporal multiscale methods for composite structures have recently been described by Fish (2011) including concurrent and information-passing schemes, block cycles and temporal homogenization approaches. Another excellent overview on multiscale simulations was made by Lu and Kaxiras (2005). Other recent studies (Kwon, 2004; Fish, 2011; Lu and Kaxiras, 2005) have proposed the use of the molecular dynamic analysis at nano-scale level, Representative Volume Elements (RVE) at micro-scale level and structural elements (e.g. solids, beams, plates or shells) at macro-scale level. Various multiscale linear and non-linear techniques can be found in literature for different loading configurations, focused on the prediction of failure processes (Zhang and Zhang, 2010; Gonzalez and LLorca, 2006). Multiscale approaches have been exploited to examine the failure behavior of fiber-reinforced laminates subjected to static loading conditions in Alfaro et al. (2011). The 'Generalized Method of Cell' (GMC) developed by Paley and Aboudi (Aboudi, 1991; Paley and Aboudi, 1992; Aboudi, 1994) considers fiber and matrix subcells as periodic repeating unit cells or Representative Volume Elements. GMC was used by Pineda and Waas for the multiscale failure analysis of laminated composite panels subjected to blast loads (Pineda and Waas, 2009) and for the progressive damage and failure modeling of notched laminated fiber reinforced composites (Pineda et al., 2009). An accurate GMC description can be found in Arnold et al. (1999). Two-and three-scale domain decompositions were used by Allix et al. (2011) for delamination analysis. A laminated composite structure was divided into two meso-constituents-substructures and interfaces-whose behavior was derived from the homogenization of micromodels. A two-level domain decomposition method was proposed by Ladeveze et al. (2001) as a computational strategy for the analysis of structures described up to micro-level. In this approach, the unknowns are split into a set of macroscopic quantities, related to the macro-scale, and a set of additive quantities related to the micro-scale. The LATIN method was used as the iterative strategy. This approach was tested on fiber-reinforced composite and honeycombs under the assumption of plane strains. Some applications on the damage micro-model of fiber-reinforced laminated composites were reported in Ladeveze and Nouy (2003) and Ladeveze et al. (2006).

The most critical issues of many multiscale approaches proposed in literature are related to the high computational costs required (in some cases hundreds of million of degrees of freedom) and the need for material properties at nano-, micro- and macro-scale. These aspects can affect the reliability and applicability of these approaches.

The method proposed in this paper is referred to as *component-wise* and it is based on higher-order 1D models. 'Component-wise' means that each typical component of a composite structures (i.e. layers, fibers and matrices) can be separately modeled by means of a unique formulation. Moreover, in a given model, different scale components can be used simultaneously, that is, homogenized laminates or laminae can be interfaced with fibers and matrices. This permits us to tune the model capabilities by (1) choosing in which portion of the structure a more detailed model has to be used; (2) setting the order of the structural model to be used. A description of the present model capabilities is provided in Fig. 1 where different components (layers, fibers and matrices) are assembled. Such a model could be seen as a 'global–local' model since it can be used either to create a *global* model by considering the full laminate or to obtain a *local* model to detect accurate strain/stress distributions in those parts of the structure which could be most likely affected by failure. In other words, the present modeling approach permits us to obtain progressively refined models up to the fiber and matrix dimensions.

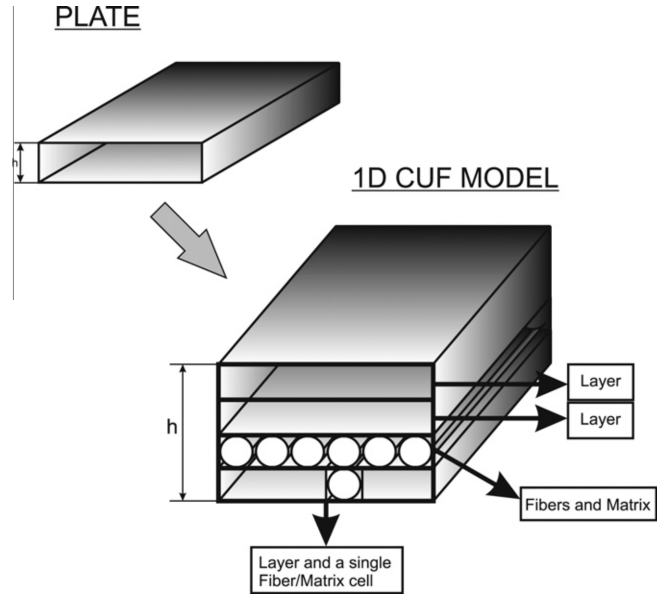

Fig. 1. Component-wise approach for layers, fibers and matrices.

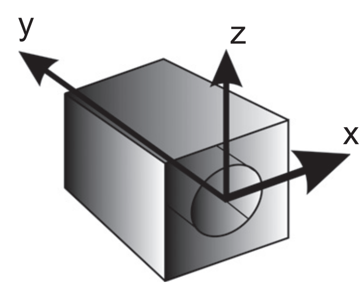

Fig. 2. Coordinate frame.

The models adopted in this paper were derived through the Carrera Unified Formulation (CUF). In the framework of CUF, it is possible to model laminates, fibers and matrices using only 1D elements, with a significant reduction of DOFs involved. Laminate's inhomogeneity and anisotropy are accounted for by separately modeling each component at its own scale level. CUF 1D models have recently been developed (Carrera and Giunta, 2010; Carrera et al., 2011a) and two classes of models were proposed, the Taylor-expansion class (TE) and the Lagrange-expansion class (LE). TE models exploit *N-order* Taylor-like polynomials to define the displacement field above the cross-section with N as a free parameter of the formulation. Static (Carrera et al., 2010a,b; Carrera et al., 2012) and free-vibration analyses (Carrera et al., 2011b; Carrera et al., in press; Petrolo et al., in press) showed the strength of CUF 1D models in dealing with arbitrary geometries, thin-walled structures and local effects. Moreover, asymptotic-like analysis leading to reduced refined models was carried out by Carrera and Petrolo (2011).

The LE class is based on Lagrange-like polynomials to discretize the cross-section displacement field. LE models have only pure displacement variables. Static analysis on isotropic (Carrera and Petrolo, 2012a) and composite structures (Carrera and Petrolo,

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