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A novel approach based on ALE and delamination fracture mechanics for multilayered composite beams

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ABSTRACT

A novel approach able to predict debonding or fracture phenomena in multilayered composite beams is proposed. The structural model is based on the first-order shear deformable laminated beam theory and moving mesh strategy developed in the framework of Arbitrary Lagrangian–Eulerian (ALE) formulation. The former is utilized to evaluate fracture parameters by using a multilayer approach, in which a low number of interface elements are introduced along the thickness, whereas the latter is utilized to reproduce crack tip motion due to the crack extension produced by moving boundaries. The model is able to avoid computational complexities introduced by an explicit crack representation in bi-dimensional structures, in which typically high computational efforts are expected for handling moving boundaries. To this aim, a moving mesh strategy is proposed for the first time in the context of beam modeling based on a multilayered configuration. Such an approach, essentially based on ALE formulation, is able to reproduce interfacial crack paths by using a low number of computational elements. The numerical method is proposed in the framework of the finite element formulation for a quasi-static or dynamic evolution of the crack tip front. In order to investigate the accuracy and to validate the proposed methodology, comparisons with experimental data and existing formulations available from the literature are developed. Moreover, a parametric study in the framework of dynamic fracture is developed to investigate the capability of the proposed model to reproduce more complex loading cases.

1. Introduction

Multilayered composites are frequently utilized because of their enhanced characteristics such as durability, excellent resistance and low weight. However, such structures are affected by interfacial debonding phenomena, which may cause strong reductions of the design load-carrying capacity with catastrophic failure modes [1]. In order to reproduce explicit debonding mechanisms, many methodologies are proposed in the literature, which are essentially developed with the purpose to evaluate fracture parameters and to simulate propagating and evolving interfacial discontinuities. Actually, crack initiation and evolution during the debonding mechanisms can be predicted on the basis of Weak or Strong Discontinuity Methods, namely WDM or SDM, respectively [2–4]. From the computational point of view, WDMs utilize interface elements on the cracked faces, introducing local traction-separation forces along the cracked faces to identify the Fracture Process Zone (FPZ) [5,6]. Specific constitutive relationships should be defined to reproduce correctly the crack evolution, especially in presence of large-scale bridging mechanisms [7]. However, as far as crack tip advances, the system of equations, becomes ill-posed and localization instabilities as well as spurious mesh sensitivity phenomena may affect the numerical modeling. Therefore, in order to accurately predict the crack growth phenomena a detailed finite element mesh at the crack tip front is strongly required [8,9]. Alternatively, methods based on SDMs are developed in the framework of Linear Elastic Fracture Mechanics (LEFM), in which it is supposed that the region affected by the crack front is considered to be small enough in comparison to the characteristic length of the FPZ. In this framework, Virtual Crack Closure Technique (VCCT), *J*-integral procedure or Global Energy Change methodology are typically utilized to predict the fracture parameters [10–12]. However, in such approaches, high computational costs are expected in the evaluation of the fracture parameters during the interfacial debonding phenomena in both initiation and evolution phases. Moreover, the approaches developed in the framework of WDMs or SDMs, are based on an explicit geometric crack representation, whose evolution should be defined by proper numerical

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procedures developed with the purpose to reproduce the crack motion. In principle, most of the classical models were concerned to analyze debonding phenomena by using node decoupling or splitting techniques, in which the crack motion was simulated by changing interelement continuity between mesh elements [13]. In this context, the crack evolution is much influenced by the crack size around the crack tip front as well as the topology of the mesh elements. In this framework, standard Finite Element Method (FEM) or Boundary Element Method (BEM) methods can be easily employed, because of their simplicity to reproduce the crack growth. However, updated mesh methods based on automatic remeshing, adaptive techniques and iterative procedures are typically utilized to reproduce the evolving crack geometry. Moreover, strong computational methods are much required in the definition of the fracture parameters and in the crack path identification to minimize the computational costs involved analyses [14–16].

Alternatively to classical methodology, formulation able to predict the crack growth based on meshless approaches can be recovered in the literature [17]. To this aim, Galerkin-based methods have been developed to evaluate fracture parameters, by using weighted approximation functions based on moving lest-square methods [18]. Such methodologies avoid node connectivity, remeshing procedures or distortions of the nodal points produced by the internal moving discontinuities, but they are affected by several difficulties to enforce essential boundary conditions in the numerical solution [19]. Moreover, the accuracy in the definition of fracture parameters is much influenced by the mesh pattern utilized in the numerical point grid.

Refined numerical methods can be also recovered by using discrete element methods (DEM), which are formulated on a length scale smaller than the one adopted by models developed in the framework of continuum mechanics [20]. In particular, such analyses are developed in terms of atomistic or particle representations, introducing equivalent actions to simulate micromechanical damage mechanisms, inter-particle strengths and toughnesses between each element. Such approach correctly reproduces the actual discontinuities between each element and their evolution during the crack propagation [21]. However, in light of a large number of variables required to simulate the debonding phenomena, high computational costs as well as mesh dependence behaviors affect the numerical solution. Moreover, the evolving discontinuities are defined by constitutive damage laws based on the material behavior of atomistic or quasicontinuum length scales, whose mechanical parameters are quite difficult to be identified from the experimental point of view [22,23]. Finally, debonding phenomena can be simulated by using numerical methods, which do not introduce an explicit representation of the crack geometry, but reproduce the presence of internal discontinuity by means of embedded specialized elements with enriching finite element approximations. Such methods, known in the literature as X-FEM or G-FEM, have received much attention, in relationship to their ability to describe cracked domains independently of the mesh involved in the numerical modeling [24]. However, some points, such as the identification of the cracked regions, the integration procedures on the enriched elements and the definition of the interpolation functions, require further analyses for the complete identification and utilization in practical applications [25].

In the proposed formulation, a new methodology based on the combination of fracture mechanics and moving mesh strategy is proposed to reproduce debonding phenomena in composite multilayered structures. The moving mesh method, frequently utilized in fluid mechanics, is here proposed in the framework of structural mechanics and, specifically, for multilayered beam models. In this context, the geometry variation produced by the evolution of crack discontinuities is based on the Arbitrary Lagrangian–Eulerian (ALE) formulation [26,27]. The nodes of the computational mesh are moved in such a way to reduce mesh distortions by using rezoning techniques, taking into account debonding phenomena on the basis of the predicted fracture variables. Despite existing models available from the literature, the proposed formulation avoids difficulties concerning the recourse to automatic remeshing procedures, which are typically utilized in the cases of an arbitrary growth crack. In order to verify the consistency of the proposed formulation, comparisons with experimental and numerical results for several laminated structures and loading schemes are developed. Moreover, a parametric study in the framework of a dynamic crack growth is developed to verify the capabilities of the proposed modeling to predict the amplification effects produced by the loading rate.

2. ALE formulation for beam modeling

In ALE formulation, it is required to describe the motion of the mesh points, which, are, typically, disconnected from the ones involved in the material point coordinates. In the framework of beam modeling, the mesh motion is prescribed by assuming one dimensional domain, which may be defined by straight or curvilinear coordinates. According to Lagrangian description, the mesh points are coincident with the material ones. The mesh motion can be defined by a family of mappings φ, which, at a generic t, associates each point ξ of the material or Lagrangian configuration Ω_L, the position of the particle X in the current configurationΩ_E (Fig. 1):

$$\varphi : \Omega_L \times [t_0, T] \rightarrow \Omega_E \times [t_0, T] \quad X = \varphi(\xi, t) \tag{1}$$

where X is the position of the particle in the current configuration, Ω_L is the Lagrangian configuration, Ω_E is the current configuration, ξ is the position of the material point in the initial configuration, T and t_0 define the observation period and the corresponding initial time. According to ALE formulation, the mesh motion can be described in the initial, current or referential configurations. In particular, it is introduced a family of mappings (ζ), which associates to a point r of the referential configuration a point X in the current configuration:

$$\zeta : \Omega_R \times [t_0, T] \rightarrow \Omega_E \times [t_0, T], \quad X = \zeta(r, t), \tag{2}$$

where ζ is assumed to be an homeomorphism, i.e. differentiable almost everywhere in $[t_0,T]$.

In the present case, the structure during the crack growth at the time t occupies a subdomain, which is assumed to be included in the one defined by the referential configuration at the time t_0, namely $\Omega_{L,E} \subset \Omega_R$. The transformation rules between material and referential configurations and the corresponding inverse relationship are written as a function of the mapping ζ by means of the following expressions:

$$J = \frac{dX}{dr} = \frac{d}{dr}\zeta(r, t), \quad J^{-1} = \frac{dr}{dX} = \frac{d}{dX}\zeta^{-1}(r, t), \tag{3}$$

where $J = dX/dr$ and $J^{-1} = dr/dX$ are the Jacobian of the transformation and its inverse, respectively. Moreover, the material and referential time derivatives of a generic function f, are defined as the time rate of change of the function with X and r fixed, respectively, and are expressed as:

$$\dot{f} = \frac{d}{dt} f(X, t)|_X, \quad f' = \frac{\partial}{\partial t} f(r, t)|_r. \tag{4}$$

where the *dot* and the *prime* define the material and referential derivatives, respectively. Therefore, the relative motion between