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A moving interface finite element formulation for layered structures

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ABSTRACT

A computational formulation based on moving mesh methodology and interface modeling able to simulate debonding mechanisms in multilayered composite beams is proposed. The approach reproduces quasi-static and fast crack propagation in layered structures and, despite existing models available in the literature, a reduced number of finite elements is required to reproduce debonding mechanisms. The theoretical formulation is based on Arbitrary Lagrangian–Eulerian (ALE) methodology and cohesive interface elements, in which weak based moving connections are implemented by using a finite element formulation. In this framework, only the nodes of the computational mesh of the interface region are moved on the basis of the predicted fracture variables, reducing mesh distortions by using continuous rezoning procedures. The use of moving mesh methodology in the proposed model is able to introduce nonlinear interface elements in a small region containing the process zone, reducing the numerical complexities and efforts, typically involved in standard cohesive approach. The analysis is proposed also in a non-stationary crack growth framework, in which the influence of time dependence and the inertial forces are taken into account. In order to verify the accuracy and to validate the proposed methodology, comparisons with existing formulations available from the literature for several cases involving single and multiple debonding mechanisms are proposed. Moreover, a parametric study in terms of mesh sensitivity, robustness and accuracy of the solution is developed.

1. Introduction

Debonding phenomena may affect several classes of structures ranging from thin film, layered materials, composite laminates or strengthened RC beams. In any cases, damage phenomena strongly reduce the structural integrity, leading to catastrophic failure mechanics, which are essentially dynamic in nature [1]. In order to reproduce, correctly, interfacial mechanisms, a fundamental task to be achieved is to understand whenever the crack growth is possible, and, in case, to investigate the identification of the debonding path, the speed and the progressive stiffness reduction at macroscopic level. Interfacial cracks can be considered as internal discontinuities, which can be analyzed by means of implicit or explicit crack representations [2]. Implicit crack formulations are essentially based on continuum models, in which constitutive relationships are introduced in the governing equations to predict stiffness reductions. However, such modeling does not provide any information about the length scale, which is much important to describe fracture phenomena; moreover, it is unable to capture the formation of few dominant cracks leading to failure mechanisms. In this framework, an accurate choice of the mesh discretization is required, which is typically adopted in such a way that the mesh spacing coincides with the internal length involved by the material discontinuities [3]. Alternatively, regularization methods should be used, in which the effects produced by internal discontinuities are incorporated in the constitutive model, leading to relatively complex numerical approaches, which require fine meshes in proximity of the regularized region [4]. It is worth noting that, the mesh enrichment partly reduces the ill-posedness of the governing equations, which still remains an important problem to be investigated. As a consequence, in the literature discrete models were preferred to continuum approaches. In terms of modeling, Cohesive Zone Method (CZM) is widely used to reproduce fracture phenomena, in which interface elements with a softening constitutive relationship are inserted in the finite element mesh [5]. The cohesive approach was firstly developed, alternatively, to Fracture Mechanics, by introducing the possibility to mitigate stress singularity and to simulate large scale decohesion phenomena. In this framework, several models are

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Nomenclature

a	initial crack length
B	width of the specimen
G_{I}	energy release rate mode I
G_{II}	energy release rate mode II
G_{IC}	critical strain energy release rate mode I
G_{IIC}	critical strain energy release rate mode II
g_T^k	crack growth function
H	thickness of the specimen
L	length of the specimen
T_n^c	critical cohesive stress mode I
T_t^c	critical cohesive stress mode II
V_{s}	shear wave speed
Δ_n^0	initial opening relative displacement
Δ_n^c	critical opening relative displacement
Δ_t^0	initial transverse relative displacement
Δ_t^c	critical transverse relative displacement
$\Delta_{n,t}^{c(\mathrm{dyn})}$	crack growth function
Γ_{i}	internal discontinues
Ω	interface region
Ω_{deb}	debonding region
Ω_{ad}	fixed region
X_T^k	position of the crack tip front of the kth debonded interface

proposed in the literature, which are mainly classified as either nonpotential or potential-based models [6]. In the former, explicit relationships of the traction–separation laws, which identify fracture behavior in presence of pure or mixed mode loading conditions are utilized, whereas the latter is based on potential functions, whose derivatives provide the tractions and the constitute relationships over the fracture process. However, CZM requires a relatively dense mesh when advanced or complex structures are analyzed. Moreover, the presence of interface elements modifies the total stiffness of the structure, especially in proximity of the crack tip, leading to spurious traction oscillations and numerical problems with erroneous crack path in the solution [7]. The use of CZM was generalized, introducing adaptive interface elements at each interelement boundaries of the continuum or throughout the calculation, i.e. dynamically into the mesh, as far as a local stress criterion for crack initiation is satisfied [8]. Such modeling is known in the literature as extrinsic cohesive model. However, the abrupt introduction of cohesive surfaces may lead to numerical problems and unrealistic predictions, especially in dynamics, in relationship to the initial rigid behavior of the cohesive constitutive modeling [9,10]. Alternatively, models developed in the framework of Strong Discontinuity Approach (SDA), based on discrete or smeared crack assumptions, are proposed, in which nodal enrichment and the partition of unity concepts are utilized for fracture modeling [11]. However, such methods, known in the literature as X-FEM or G-FEM, may be affected by numerical complexities, such as the identification of the cracked regions, the integration procedures on the enriched elements, the definition of the interpolation functions.

Most of the formulations available from the literature are mainly devoted to identify fracture parameters involving the creation of new surfaces or the conditions which correspond to the crack growth. However, complexities concerning numerical, theoretical or analytical aspects are well known when it is required to reproduce moving discontinuities in continuum media. As a matter of fact, mesh dependent problems, ill-posedness of the governing equations, spurious sensitivity effects typically affect the above referred formulations [12,13]. In order to avoid such problems, a combined formulation based on fracture and moving mesh methodology is proposed. In particular, the former is able to evaluate the variables, which govern the conditions concerning the crack initiation and growth, whereas the latter is utilized to simulate the evolution of the crack growth by means of ALE formulation [3,14,15]. It is worth noting that the use of moving mesh method, combined with regularization and smoothing techniques, appears to be quite efficient to reproduce the evolution of moving discontinuities. However, existing models based on ALE and Fracture mechanics [3,14,16] are based on a full coupling of the governing equations arising in both structural and ALE domain. In this framework, material and mesh points in the structural domain produce convective contributions and thus non standard terms in both inertial and internal forces. In the proposed formulation, the use of a weak discontinuity approach avoids the modification of the governing equations arising from the structural model and thus a lower complexity in the governing equations and the numerical computation is expected. In order to verify the consistency of the proposed formulation, comparisons with existing formulations for several cases involving single and multiple delaminations are developed. Moreover, a parametric study in the framework of mesh characteristics, influence of the dynamic effects is developed to verify the capabilities of the proposed modeling. The outline of the paper is as follows. Section 2 presents the formulation of the governing equations for the ALE and interface approach, whereas in Section 3 the numerical implementation of the finite element model is reported. Finally, comparisons and parametric results to investigate the dynamic characteristics of the debonding phenomena are proposed in Section 4.

2. Theoretical formulation of the moving formulation

In this section, the theoretical formulation will be presented, starting from the definition of the moving interface model. Subsequently, governing equations of the multilayered formulation and cohesive traction–separation laws will be discussed.

2.1. ALE formulation and interface approach

The proposed model is presented in the framework layered structures, in which thin layers are connected through adhesive elements. The theoretical formulation is based on a multilayered shear deformable beam and a moving interface approach (Fig. 1). The former is able to reproduce 2D solution by introducing a low number of finite elements along the thickness of the structure, whereas the latter is able to simulate the crack tip motion on the basis of the adopted growth criterion [17]. However, the proposed interface model is quite general to be implemented also in the framework of plane stress/strain formulations. Moreover, the interfacial defects are assumed to propagate along the interfaces between the laminas, which are considered in this analysis as weak planes where the delaminations are able to growth [18]. This assumption can be motivated from a physical point of view, since