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A Moving Cohesive Mesh Formulation to Predict Debonding Phenomena in Layered Structures

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ABSTRACT

A new numerical formulation, which combines the Cohesive Zone Model (CZM) approach with the Arbitrary Lagrangian-Eulerian (ALE) methodology to investigate the crack onset and evolution of multilayer composite beams is presented. The CZM approach is used to calculate the main variables, which governs the conditions of onset and propagations of delamination, whereas the ALE formulation is employed to simulate the evolution of the crack growth. In spite of numerical methodologies based on pure CZM, the proposed formulation guarantees lower computational efforts since a reduced number of finite elements is required to reproduce delamination mechanisms. Moreover, the proposed model is able to introduce the nonlinearity only in a small region around the crack tip, whereas in the remaining one, linear equations to simulate perfect adhesion are introduced. In order to verify the accuracy and to validate the proposed formulations, comparisons with existing formulations available in literature are proposed. Moreover, a parametric study to evaluate the delamination phenomena in dynamic and the contributions arising from through-thickness reinforcements, such as Z-pin elements, is performed.

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1. Introduction

Composite materials are widely used from aerospace industry to civil engineering [1–3]. Typically, composite materials are fabricated in the form of multilayer elements, which are obtained by stacking together several laminate plies [4].

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_f^k	crack growth function
T_n^c	critical cohesive stress mode I
T_t^c	critical cohesive stress mode II
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
$\Delta_{n,t}^{c(dyn)}$	dynamic critical opening or transverse relative displacement

In particular, the fibers of each plies are oriented in different ways to improve in-plane mechanic behavior. The result is a high performance element, which ensures a good mechanical properties and a very low weight. However, multilayer composites exhibit a low resistance against interlaminar delamination [5,6]. Interlaminar delamination is a quite dangerous damage mechanism for multilayer composites, since it leads to a progressive deterioration of the structural integrity [7]. Delamination problems have been subjected to extensive investigations to analyze the onset of cracks as well as the evolution of crack front. At earlier, investigations are performed in the framework of linear elastic fracture mechanics (LEFM) theory. In this framework, closed form analytical solutions are developed for regular geometries and limited load cases [8,9]. LEFM models are based on continuum formulations, in which concepts of stress intensity factor and the energy release rate are employed to investigate onset and the propagation of the crack front. However, LEFM models presume the existence of an initial crack prior of the analysis. Moreover, a relatively small size of the non-linear zone at crack tip compared to the overall dimensions of the specimens is required. Alternatively to LEFM models, the Cohesive Zone Model (CZM) approach has emerged as a powerful tool to analyze composite delamination problems [10–12]. Unlike the classic LEFM models, the cohesive approach allows a unique description of both onset and propagation of delamination processes. Basically, the cohesive zone model identifies two surfaces that are held together by means of cohesive traction forces. The cohesive traction forces are related to the separation displacements between the cohesive surfaces by means of a cohesive laws, typically based on a softening mechanical behavior. The CZM is a simple technique that may easily incorporated into finite element numerical models to investigate any kind of fracture phenomena. This can be obtained simply defining interface elements and a constitutive relationship. Usually, adaptive interface elements are modelled at each interelement edge of the continuum. Each interface element become active when a crack initation criterion is satisfied. However, CZMs, in certain cases, may suffer of numerical problem due to mesh dependence, computing inefficiency, sensitivity to the element aspect ratio. These issues may be partially addressed adopting a very fine discretization at the crack tip front. However, the corresponding numerical model will be characterized by a high number of variable, which contribute to increase calculation times. An alternative way to reduce mesh dependence and, at the same time, to obtain an efficient and robust model is to combine the CZMs with the Arbitrary Lagrangiane-Eulerian (ALE) methodology [13,14]. The ALE approach have been efficiently applied to analyze plane stress of multilayered beam schemes for both static and dynamic problems [15,16]. The ALE methodology contributes to develop accurate analysis models with reduced numerical complexities and efforts. The main aim of the present paper is to propose an advanced numerical model based on CZMs and ALE formulations able to investigate the delamination problems in multilayer composite beams. In this context, the CZM approach is used to calculate the main variables which governs the conditions of onset and propagation of initial defects, whereas, the ALE formulation is employed to simulate the crack growth by modifying geometrical positions of the computational points. In order to verify the consistency of the proposed model, comparisons with existing formulations for several cases involving delamination in a mode I and mixed mode are presented. At first, validations are proposed in a static context. Afterwards, a sensitivity study on the dynamic effects and mesh characteristics is developed to verify the capabilities of the proposed modeling. Finally, in order to assess the flexibility of the proposed model to investigate more complex cases, numerical analyses are developed to investigate multilayer composite beams reinforced with through-thickness elements, such as Z-pins elements [17].

2. Formulation of the model: Theoretical and numerical implementation

The proposed model is presented in the framework of layered structures, in which each layers is modelled by means beam elements consistent with the Timoshenko theory, whereas at each interface an ALE-cohesive element is introduced to simulate both delamination onset and growth. A synoptic representation of the proposed model and the Traction Separation Law (TLS) introduced in the interface are shown in Fig. 1.

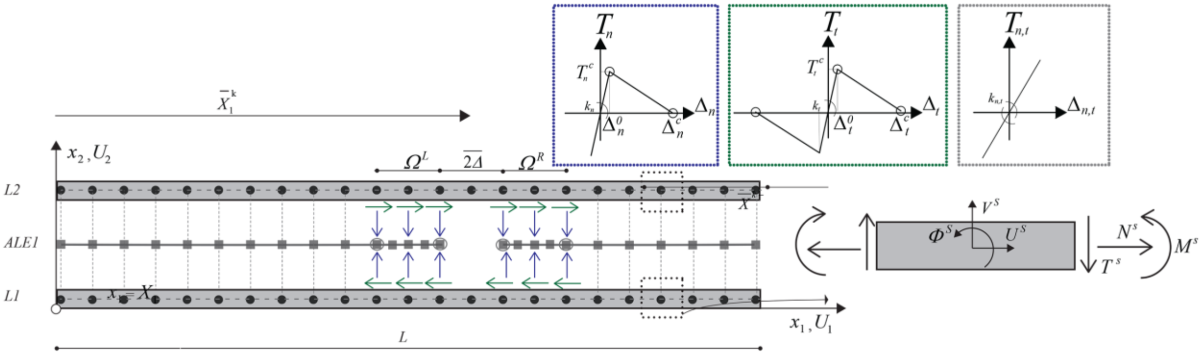


Fig.1. General representation of the laminate structure and of TSL.

2.1. Crack onset position

At this phase of the numerical procedure, the goal is to define a strategy able to identify the onset condition and itself position. To this end, a crack function is adopted with the aim to capture the onset condition under a mixed mode of delamination. In the proposed formulation the crack function is based on the ratio between the ERR components $\left(G_I, G_{II}\right)$ and their critical value $\left(G_{IC}, G_{IIC}\right)$:

$$g_f^k\left(X_1^k\right) = \left(\frac{G_I\left(X_1^k\right)}{G_{IC}}\right)^{\frac{r}{2}} + \left(\frac{G_{II}\left(X_1^k\right)}{G_{IIC}}\right)^{\frac{r}{2}} - 1 \tag{1}$$

To concern the TSL, in this work has been used a model consistent with a bilinear law which is function of critical cohesive stresses $\left(T_t^c, T_n^c\right)$, critical and initial opening or transverse relative displacements, namely $\left(\Delta_n^0, \Delta_n^c\right)$ and $\left(\Delta_n^0, \Delta_n^c\right)$. It should be noted that the proposed model is quite general and other TSL could be implemented. In order to include the rate dependent effects arising from the dynamic delamination process, a modification of Eq. (1) should be introduced. According to experimental evidences, it is supposed that the critical stress $\left(T_t^c, T_n^c\right)$ of the material is constant, whereas the critical crack opening or sliding displacement is depending to corresponding speed $\left(\dot{\Delta}_n, \dot{\Delta}_t\right)$:

$$\Delta_{n,t}^{c(dyn)} = \Delta_{n,t}^{c(st)}\left[1 + \left(\frac{\dot{\Delta}_{n,t}^{c}}{\dot{\overline{\Delta}}_{n,t}^{c}}\right)^{n}\right] \tag{2}$$

Since the onset condition is not yet reached, the numerical steps descripted earlier have been perform with the ALE elements no active. As a matter of fact, at this stage the Moving Frame can be considered coincident with the Material one, identified by the x1-x2. The location, in which the debonding onset is reached, are captured searching the $\overline{X}_{1,i}^k$ position in which Eq(1) show a null value:

$$g_f^k\left(\overline{X}_{1,i}^k\right) = 0 \quad with\ 0 \le \overline{X}_{1,i}^k \le L, i = 1, \mathrm{N}_d^k \tag{3}$$

where the index *i* represents the number of the *i*-th debonding mechanism potentially activated at the *k*-th interface and N_d^k is the number of material discontinuities activated at the *k*-th interface.

2.2. Debonding growth: The ALE approach

Since the crack onset position is captured using Eq. (3), at this stage the model is subjected to a smart remeshing procedure in order to ensure accuracy in the evaluation of fracture variables around the crack tip. The main goal in this phase is to reproduce the movement of the crack tip using the ALE strategy which is able to modify the geometrical position of the computational points at the interfaces. To this end, the cohesive traction forces are introduced using a Moving Frame, identified by X1-X2 coordinates (Fig. 2). As shown in Fig.2 in order to obtained a mathematical corresponding between Referential (Ξ_R) Frame and Moving (Ξ_M) frame a mapping operator Φ is defined as follow [18].

$$\underset{\sim}{X} = \Phi\left(\underset{\sim}{\xi}, t\right) \qquad \text{with} \quad \Phi : \Xi_R \rightarrow \Xi_M \tag{4}$$

where $\underset{\sim}{\xi}$ and $\underset{\sim}{X}$ describe the positions of the computational nodes on the interface, for each time steps, in the referential and moving configurations (Fig.2).

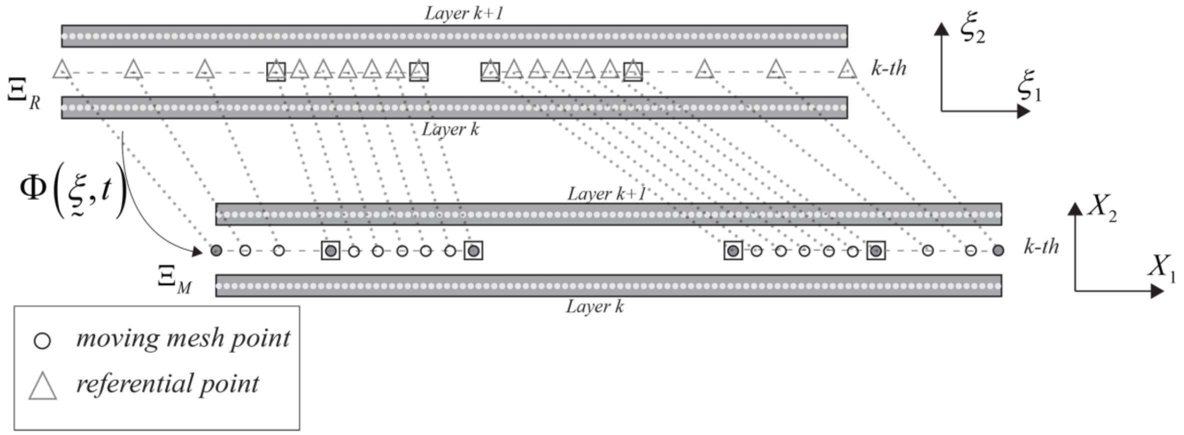


Fig. 2. Mapping between Referential and Moving frame.

The proposed model takes the form of a set of nonlinear differential equations implemented by using a customized FE subroutine in the framework of COMSOL Multiphysics [18]. In particular, the analysis is based on several steps, which are connected by using stop/restart procedures. In particular, the built-in Newton-Raphson or implicit transient analyses based backward differentiation formula (BDF) for static and dynamic analyses are employed. These are managed by means of external script files based on stop condition for crack initiation and restart/remeshing procedures for the activation of moving interface elements A synoptic representation of the numerical procedure, implemented in the FE environmental program, is shown in Fig. 3

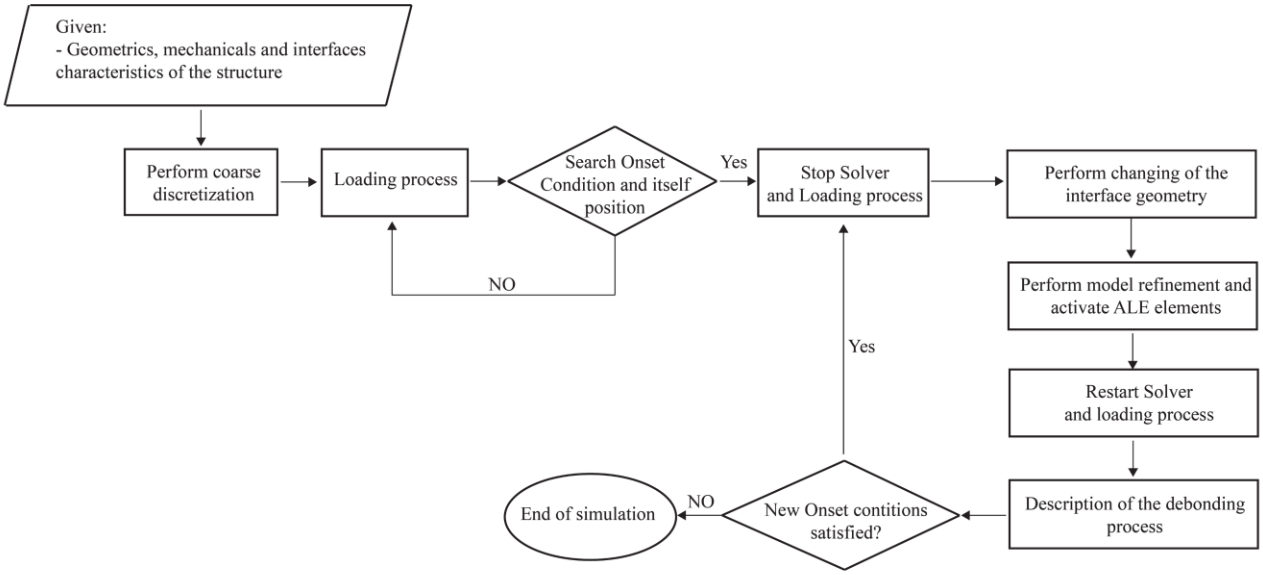
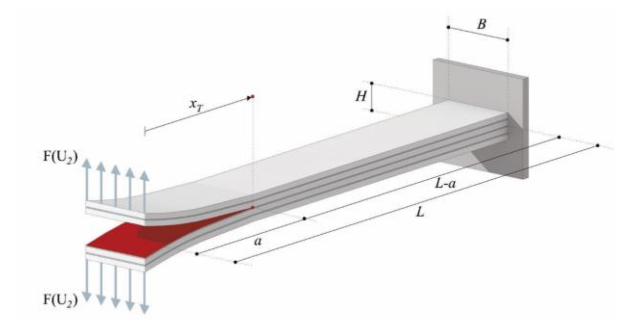


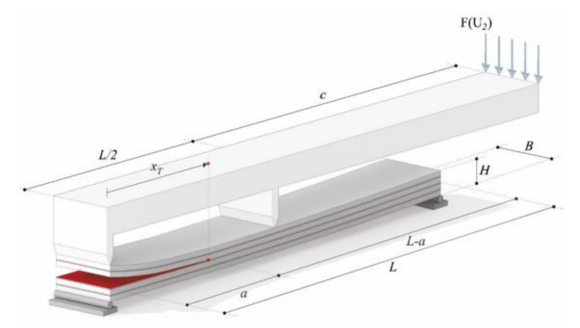
Fig. 3. Representation of the Flow chart implemented in COMSOL Multiphysics.

3. Results

At first, the accuracy of the proposed approach has been assessed by means of comparisons with numerical and experimental results reported in literature. Fig.s 4a-b show the results relatives to classical DCB and MMB loading schemes, respectively. For both loading schemes, the plots of load-relative displacement and load-crack tip grow are reported. In particular, the predictions of the proposed model are compared with the ones reported in Ref.s [19] and [20], which have analyzed the same problems by means of a refined X-FEM modelling and analytical solutions, respectively. Note that, analytical results, reported in [18] are not provided in the whole range of observation. The input data for the analyses are reported in Table 1. Results show that the proposed model is in accordance with results reported in the literature. It is worth nothing that, in Ref. [19], the X-FEM model is based on an extremely fine mesh. In particular, 45000 four-node bilinear plane strain quadrilateral elements with 0.1 edge length have been adopted to improve the accuracy. This lead to a numerical model involving 46469 Dofs. Contrarily, the proposed model employs on a uniform mesh of 2075 elements with 0.2 edge length.Then, the number of Dofs is equal to 6234, which ensures a reduced computational time. Fig. 5a reports parametric results in terms of mesh properties. The main aim is to analyze the solution trend for two different mesh discretizations, namely S1 and S2. In particular, uniform mesh configurations for the layer and interface with values of element length equal to $\Delta D/L = 1/150$ and $\Delta D/L = 2/150$ are adopted, respectively, for S1 and S2. However, previous discretizations are considered in the debonding zone, where at least five elements are introduced. The analysis has focused on the evolution of the load-displacement curves Results show that the coarsest mesh (S1) leads to several oscillations in the development of the load-displacement curves. This trend decreases employing the mesh S2, since the solution converges to the refined one.

Table 1
Geometrical and mechanical properties of the laminates.





L [mm]	B [mm]	a [mm]	H [mm]	E_1 [GPa]	E_1=E_2 [GPa]	G_{12} [GPa]	ν	G_{IC} [Nmm^{-1}]	G_{IIC} [Nmm^{-1}]
150	*20*	*35*	*3.1*	*120*	*10.5*	*5.25*	*0.3*	*0.260*	*1.002*
T_n^c [MPa]	Δ_n^0 [mm]	Δ_n^c [mm]	T_t^c [MPa]	Δ_t^0 [mm]	Δ_t^c [mm]	$\bar{\dot{\Delta}}_n^c$ [ms^{-1}]	$\bar{\dot{\Delta}}_t^c$ [ms^{-1}]	n	P [kg/m^3]
30	*0.0057*	*0.0173*	*60*	*0.00334*	*0.0334*	*2.5*	*2.5*	*1*	*1500*

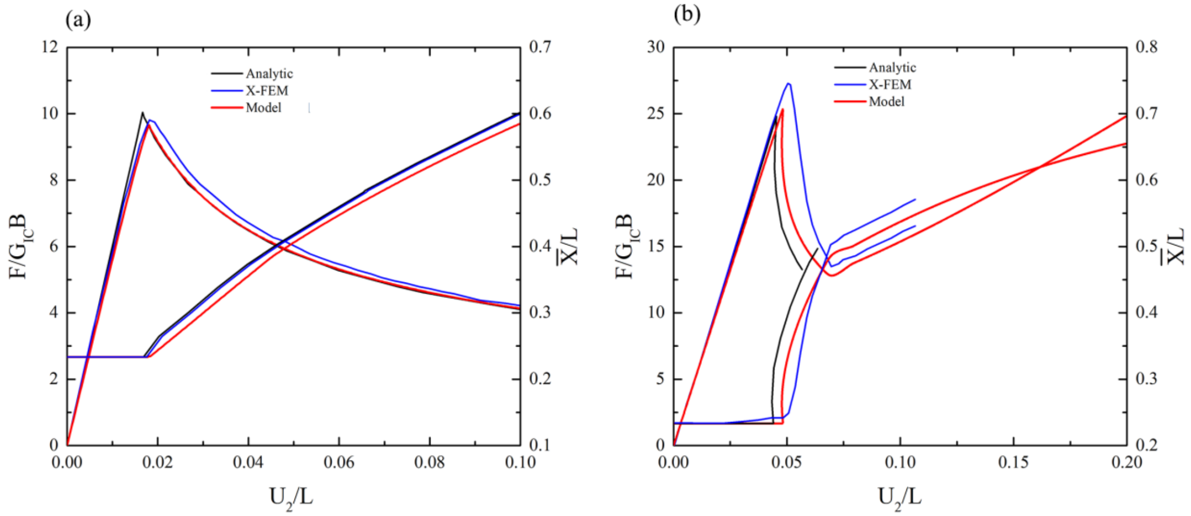


Fig. 4. Comparison results: Loading curve and crack tip position for DCB test (a) and MMB test (b).

Previous results are obtained by means of quasi-static analyses, in which inertial forces and loading rate effects have been neglected. However, dynamic effects may lead to different predictions of the structural behavior. In order to investigate the structural behavior of composite beams due to dynamic effects, the proposed model was investigated in a dynamic context. To this end, the TSL of the cohesive elements has been generalized in a dynamic context. In particular, inertial effects arising from the multilayered beam structure and those involved in the delamination process are considered. The loading rate follows a time dependent function, which is composed by an initial linear ramp curve and a subsequent constant function. The linear ramp curve takes place in the range from 0 to t=t_0, where t_0 is assumed to be equal to ½ of the first period of vibration (T_1). This value guarantees an adequate short time to achieve a quickly crack growth without a fluctuating behavior in the crack advance [21].

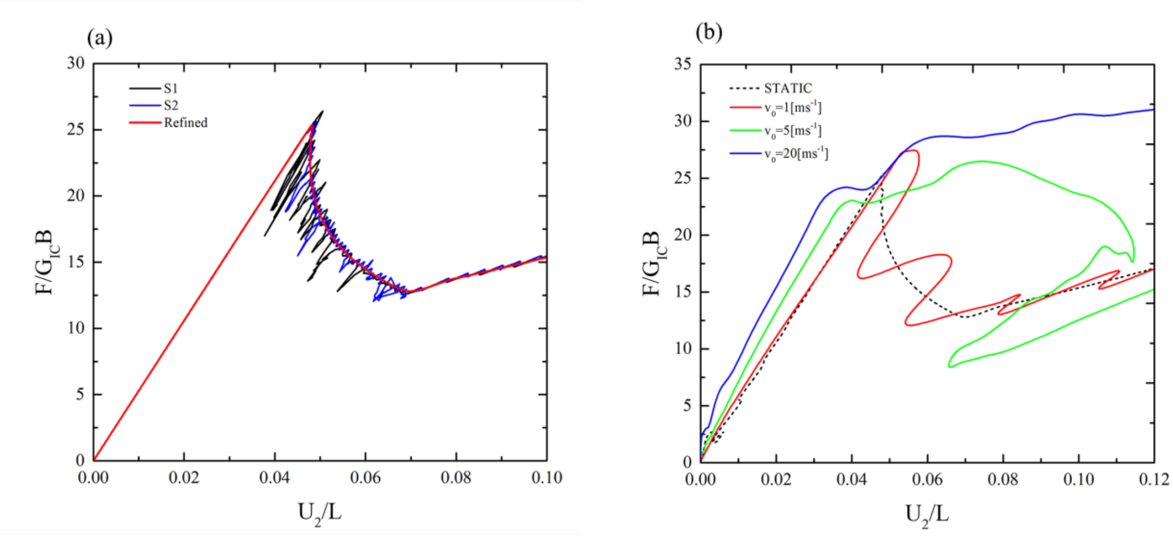


Fig. 5. Loading curve variability in terms of mesh discretization for MMB test (a); Variability of the load-displacement curves in terms of loading rate for MMB test (b).

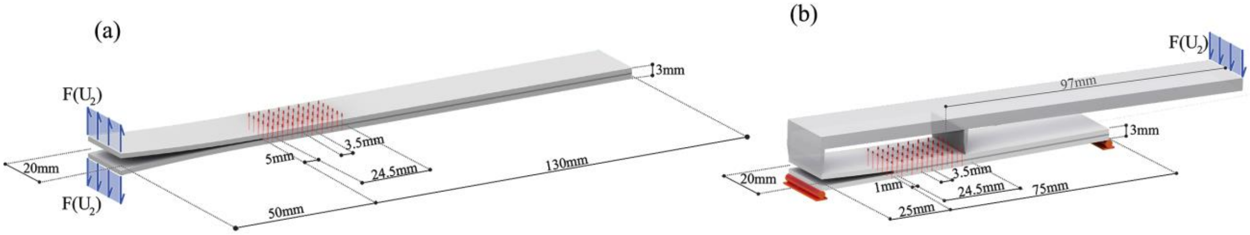


Fig. 6. DCB scheme reinforced with z-pins (a); MMB scheme reinforced with z-pins (b).

Table 2
Mechanical and interface properties of the laminate.

E_1 [GPa]	E_2=E_3 [GPa]	G_{12} [GPa]	ν	G_{IC} [Nmm^{-1}]	G_{IIC} [Nmm^{-1}]	T_n^c [MPa]	Δ_n^0 [mm]	T_t^c [MPa]	Δ_t^0 [mm]
138	*11*	*4.4*	*0.34*	*0.250*	*0.7*	*24.15*	*0.00966*	*15*	*0.006*

Table 3
Geometrical and mechanical properties of the z-pins.

P_n^c [N]	Δ_{np}^0 [mm]	Δ_{np}^c [mm]	P_t^c [N]	Δ_{tp}^0 [mm]	Δ_{tp}^c [mm]
34.5	*0.0086*	*0.88*	*45*	*0.011*	*1.2*

Fig. 5b shows the load-relative displacement curves obtained for different loading rates with reference to a MMB loading scheme. Moreover, the solution arising from the static case is also reported. The results show that the structural response of the multiplayer beams is highly affected by dynamic effects. As a matter of fact, the higher is the loading rates the larger is the difference between dynamic and static response in terms of load-displacement curves.Such prediction is in agreement with several experimental data, which have shown that in fast crack evolution, the process zone involves a larger damage zone with more dissipated energy. This aspect leads to oscillations and large values in the load-displacement curve [15].

Finally, numerical results are developed to analyze the case of multilayered composite beams reinforced with z-pins elements [17,22,23]. The geometry and the loading boundary conditions of two case studies considered are illustrated in Fig.6. Mechanical and interface properties of the laminate are reported in Tab. 2, whereas the mechanics characteristics of z-pin are illustrated in Tab. 3. According to [15], in order to described the failure process of the single z-pin a mixed mode criterion has been adopted. The main aim is to assess the flexibility of the proposed model to investigate different cases of delamination problems. Fig. 7 a-b illustrate comparisons between the proposed model, numerical [22,24] and experimental data [25] reported in literature in terms of load-relative displacement curves. In particular, Fig. 7a and Fig. 7b refer to DCB and MMB loading scheme, respectively. Results show that in both cases the proposed model is quite in agreement with numerical and experimental data. In particular, the proposed model reproduces accurately the contribution arising from the z-pins, since oscillations in the load-displacement curve, which are characteristic of z-pin reinforced laminates, are correctly simulated.

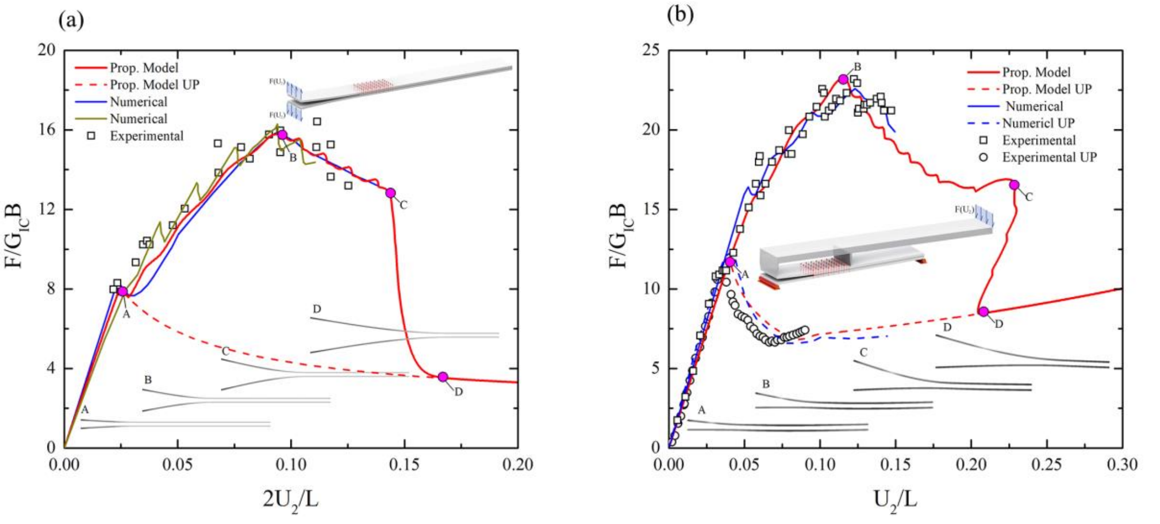


Fig. 7. Investigation on Z-pins contributions: Comparisons in terms of loading curve with experimental data and numerical results for DCB test (a) and MMB test (b).

4. Conclusions

The proposed Model is focused on a new numerical methodology able to reproduce delamination onset and growth combining the moving mesh methodology and the CZM. Compared with classical CZM, the proposed model is able to improve the computational efficiency without loss of accuracy. Several comparisons with numerical and experimental data have been developed in order to assess the reliability of the proposed formulation. From results, it transpires that the proposed model is able to accurately reproduce the structural behavior of multilayered composite beams in static and dynamic contexts. Moreover, further analyses on multilayered composite beams reinforced by means of z-pins elements have revealed that the proposed model is quite general to be applied for the analysis of any kind of delamination problem.

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