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A cohesive finite element model based ALE formulation for z-pins reinforced multilayered composite beams

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Abstract

A computational formulation able to simulate fast crack growth in multilayered composite reinforced with z-pins is proposed. In particular, in order to identify the initiation and the growth of the crack, a moving mesh strategy, based on ALE approach, is combined with a cohesive methodology, in which weak based moving connections with the boundary adjoining layers are implemented by using a finite element formulation. Contrarily, z-pin reinforced area was simulated with a deformation of a set of discrete nonlinear springs fixed to material domain. Despite existing methodologies available from the literature, the present paper proposes a computational procedure able to study the dynamic crack growth in composite structures with a relatively low computational efforts. The analysis is proposed also in a non-stationary framework, in which the influence of time dependence and the inertial forces is taken into account. In order to investigate the accuracy and to validate the proposed methodology, comparisons with experimental data and numerical results are compared. Finally, the parametric study in terms of z-pins characteristics is also developed.

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Keywords: Moving mesh methods, ALE, Cohesive elements, Layered structures

1. Introduction

Multilayered composites are frequently utilized in many structural applications. Traditional fiber composites are manufactured by stacking together a number of plies, in which the fibers are oriented to provide in-plane reinforcements for the composite. A direct consequence of this process is that no fibers are positioned across the

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laminates thickness (Greco et al., 2015). Indeed, these structures are affected by interlaminar defects which may cause strong reduction of load-carrying capacity with catastrophic failure modes (Bruno et al., 2013). To improve the delamination resistance, several through-thickness, e.g. stitching, z-fibre pinning and tufting, have been developed (Greco et al., 2015). In particular, z-pinning has attracted larger interest in its application in the aircraft structures, because it is the only through-thickness toughening technique that can be readily applied to multilayered composites materials. Indeed, when a delamination crack is propagating, z-pins provide traction forces that restrict the crack opening displacement and increase the fracture toughness (Bruno et al., 2011). In this framework there are two issues: the modeling of the interfacial crack and the z-pin reinforced area. Interfacial cracks can be considered as internal discontinuities, which can be analyzed by means of implicit or explicit crack representations (Bruno et al., 2018). Implicit crack formulations do 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 (Bruno et al., 2009). Implicit crack formulation is affected by several problems, since such modeling does not capture the formation of non-dominant fractures (Bruno et al., 2010). For these reasons, in literature, discrete models were preferred to continuum approaches. The Cohesive Zone Method (CZM) was developed alternatively to Linear Elastic Fracture Mechanics (LEFM) to simulate the debonding process in composite laminate. In the CZM interface elements with a softening constitutive relationship are inserted in the finite element mesh. The interface element is able to transfer the forces between two substructures (eg. between two laminates) until the failure criterion is satisfied. However, CZM presents computational limits, which are essentially related to the use of a dense mesh in the process zone. To avoid such problems, a formulation based on cohesive fracture and moving mesh is proposed. The cohesive law was simulated with distributed non-linear springs, in which traction separation law is used to evaluate the variables that govern the conditions concerning the crack initiation. Moreover, the crack growth is simulated by means of a moving mesh method based on ALE formulation (Funari et al., 2016). It is worth noting that in the present approach two reference coordinate systems are utilized to describe the structural and the debonding phenomena, respectively. In particular, a moving weak discontinuity approach based on ALE formulation is implemented to describe moving traction forces acting on the interface region of the laminate. Moreover, fixed (material) referential system to model the z-pin behavior and the laminate response. Therefore, the proposed model has two cohesive zone, the first defined in the mobile domain, while the second fixed to material domain. In order to verify the consistency of the proposed formulation, comparisons with existing formulations for several cases involving single and multiple delaminations under static and dynamic loading are developed. Moreover, was analyzed the behavior of proposed model when it is reinforced with inserting carbon or metallic rods in the thickness direction of laminates. The outline of the paper is as follows. Section 2 presents the formulation of the governing equations for the ALE and interface approach and the corresponding numerical implementation. Finally, comparisons and parametric results to investigate the static and dynamic characteristics of the debonding phenomena of pinned and unpinned laminates are proposed in Section 3.

2. Theoretical formulation and numerical implementation

The proposed model is presented in the framework of z-pin reinforced composite laminate. In order to reproduce such structures, the simultaneous presence of two interface approaches is considered. In particular, a moving domain is implemented to reproduce the progressive crack growth defined in the framework of interlaminar damage phenomena. Moreover, a set of fixed nonlinear springs is utilized to simulate the z-pin reinforced area and the structural problem, essentially based on the use of a shear deformable multilayered beam formulation. However, the proposed interface model is quite general to be implemented also in the framework of 2D plane stress/strain formulations. A general representation of the proposed model, the TSL of the cohesive interface and the z-pin pullout model are illustrated in Fig. 1. The multilayered is affected by N_D internal discontinuities, which are supposed to be located along the interface between two sublaminates, whereas a fixed region is assumed to be reinforced by means of z-pin elements. The main purpose of proposed model is to predict the evolution of these discontinuities and to evaluate the improvement effects provided by interlaminar reinforcements. In order to predict the evolution of such internal discontinuities, a moving mesh methodology based on ALE approach is proposed, which is

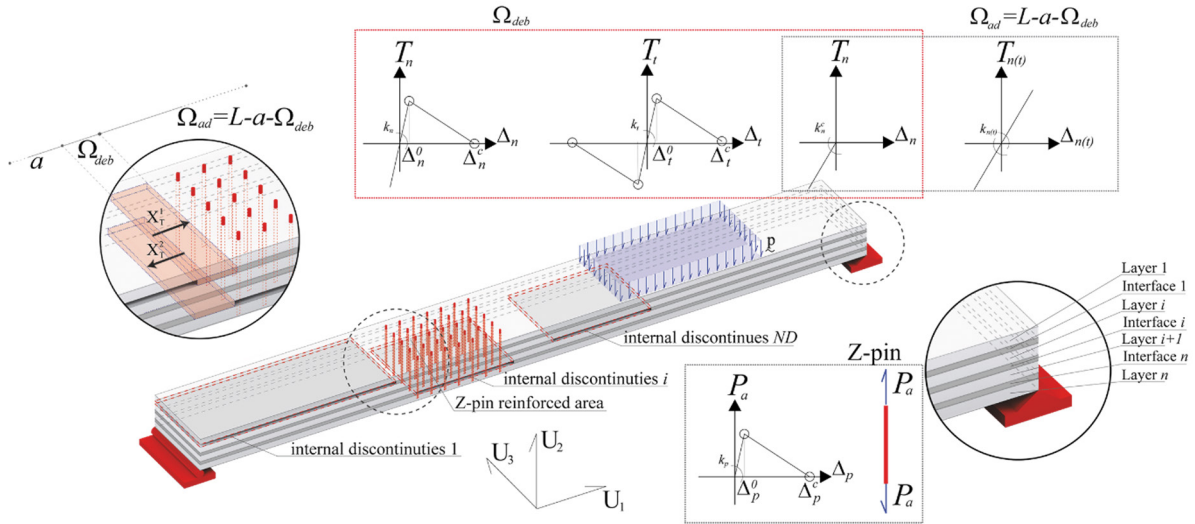


Fig. 1. Multilayered laminate structure: general representations of geometrical, TSL and z-pin pullout model.

introduced only for the interface regions, leaving the governing equations of the structural model basically unaltered. To this end, a moving coordinates to describe the mesh motion on the basis of the predicted fracture parameter is introduced, while fixed or material coordinates are used to describe structural formulation and z-pin reinforced area. In particular, ALE kinematic is based on the use of a fixed Referential frame (R), which differs from the classical Spatial (S) or Material (M) domains, respectively. In the spatial motion, the position \underline{X} of a physical particle is described by $\underline{X} = \Phi(\underline{\xi}, t)$, whereas the mesh motion is defined in terms of a fictitious referential position, namely \underline{r} . Therefore, according to ALE description the following referential maps can be introduced which identify referential, material and spatial configurations (Lonetti, (2009)):

$$\underline{X} = \Phi(\underline{\xi}, t) \qquad \underline{\xi} = \Psi(\underline{r}, t) \qquad \underline{X} = \zeta(\underline{r}, t) \tag{1}$$

where the transformation between material and referential configuration is described by the mapping Ψ . Starting from Eq.(1), in the case of onedimensional problem, material and referential derivatives can be computed introducing the related deformation gradients:

$$\frac{d}{dX} f(X, t) = \frac{d}{dr} f(X, t) \frac{dr}{dX} = \frac{d}{dr} f(X, t) J^{-1}, \tag{2}$$

where $J = dX/dr$ and $J^{-1} = dr/dX$ are the Jacobian and its inverse of the transformation, respectively.

2.1. CZM in moving domain

The interface region (Ω) is defined as the sum of a fixed portion Ω_{deb} and a variable one Ω_{ad} . In the fixed portion Ω_{deb} , the TSL is defined by a softening constitutive law, whereas in the remaining region Ω_{ad} perfect adhesion, based on linear interface elements with stiffness proportional to the penalty parameter, is introduced to impose displacement continuity along the thickness direction. In the present study, a traditional bilinear cohesive law was used for both mode I and mode II (Fig. 1). The Traction Separation Law (TSL) is defined by the following expression:

$$T(\Delta) = \begin{cases} \frac{T^c}{\Delta^0} \Delta & \Delta \leq \Delta^0 \\ T^c \left(\frac{\Delta - \Delta^c}{\Delta^0 - \Delta^c} \right) & \Delta > \Delta^0 \text{ and } \Delta < \Delta^c \end{cases} \quad (3)$$

where $(\Delta, T^c, \Delta^0, \Delta^c)$ is equal to $(\Delta_n, T_n^c, \Delta_n^0, \Delta_n^c)$ or $(\Delta_t, T_t^c, \Delta_t^0, \Delta_t^c)$ in the case of the TSL for tangential or opening modes, respectively. In particular, opening and shear traction separation laws are coupled by means of simple failure criterion, which is satisfied as far as the crack growth function g_T^k reaches the zero value, as follows:

$$g_T^k = \left(\frac{G_I}{G_{IC}} \right)^{\frac{f}{2}} + \left(\frac{G_{II}}{G_{IIC}} \right)^{\frac{f}{2}} - 1 \quad G_I = \int_0^{\Delta_n^c} T_n(\Delta_n) d\Delta_n \quad G_{II} = \int_0^{\Delta_t^c} T_t(\Delta_t) d\Delta_t \quad (4)$$

In order to include the rate dependence effects of the TSL, a modification of Eq. (4) should be achieved. According to experimental evidences, it is supposed that the critical stresses $T_{\Delta_n}^c$ or $T_{\Delta_t}^c$ of the material are constant and the critical crack opening or sliding displacements increase with the corresponding interlaminar speed, i.e. $\dot{\Delta}_n$ or $\dot{\Delta}_t$. As a consequence, an amplification of the dynamic fracture toughness is simulated, which is mainly produced by the multi-microcracking mechanisms, by means of the following relationship:

$$\Delta_{n,t}^{c(dyn)} = \Delta_{n,t}^{c(st)} \left[1 + \left(\frac{\dot{\Delta}_{n,t}^c}{\dot{\Delta}_{n,t}^c} \right)^n \right] \quad (5)$$

2.1. Z-pin pullout model

The z-pin behavior is based on a set of fixed discrete nonlinear springs based on three different phases in z-pin pullout process. In particular, at first the behavior of z-pin is linear elastic until stretching is lower than Δ_p^0 ; subsequently a progressive damage is enforced until the critical displacement is reached, namely Δ_p^c . At the end, when the value of stretching is larger than Δ_p^c , the z-pin is completely damaged and thus the traction forces tend to zero. The bilinear pullout model, reported in Fig. 1, is defined by the following expression:

$$P(\Delta_p) = \begin{cases} \frac{P_a^c}{\Delta_p^0} \Delta_p & \Delta_p \leq \Delta_p^0 \\ P_a^c \left(\frac{\Delta_p - \Delta_p^c}{\Delta_p^0 - \Delta_p^c} \right) & \Delta_p > \Delta_p^0 \text{ and } \Delta_p < \Delta_p^c \end{cases} \quad (6)$$

3. Results

The analyses are developed with reference to loading schemes based on classical DBC (opening). The loading, the boundary conditions and the geometry are illustrated in Fig. 2. The values of mechanical and geometrical properties assumed for the laminate scheme are reported in Tab. 1, whereas those concerning the cohesive zone model and z-pins characteristics are reported in Tabs. 2-3, respectively.

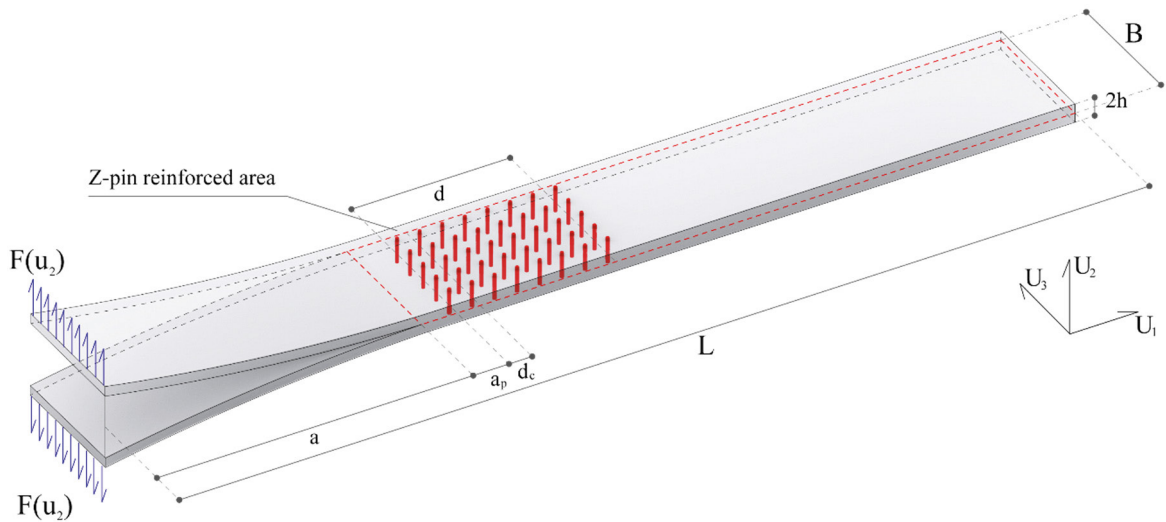


Fig. 2. Geometrical properties of the loading schemes.

Table 1. Geometrical and mechanical properties of the laminate.

n	$E_2 = E_3$ [GPa]	G_{12} [GPa]	ν	L[mm]	B[mm]	h[mm]
165	11	38	0.3	150	20	1.55
ρ [Kg/mc]	a[mm]	a_p [mm]	d[mm]	d_c [mm]	n_c	n_r
1500	50	5	24.5	3.5	8	5

Table 2. Properties of the cohesive interface.

G_{Ic} [Nmm ⁻¹]	T_n^c [MPa]	Δ_n^0 [mm]	Δ_n^c [mm]	$\bar{\Delta}_n^c$ [ms ⁻¹]	n
0.265	20	0.00265	0.0265	2.5	1

Table 2. Properties of the single discrete non linear spring (z-pin).

G_{Ic} [Nmm]	P_a [N]	Δ_p^0 [mm]	Δ_p^c [mm]
0.265	15	0.1	1.5

At first, the numerical discretization utilized for the comparisons is assumed to be uniform and with a length equal $\Delta D/L=0.2/150$, with ΔD the element length. This discretization provides a stable crack propagation. It is worth noting that the numerical model arising by Yan et al., (2003) is based on the use of 4-node bilinear plane strain quadrilateral elements. The total number of elements is approximately 13700 involving in 28400 dof. Contrarily, by using the proposed approach, the number of FE variables is strongly reduced, since an uniform discretization the mesh element length, equal to 0.2 mm, is utilized. In this configuration, the total number of elements is equal to 2000 involving 5541 dof. In Fig. 3(a) the relationship between resistance, applied displacement and crack tip position for loading scheme reported in Fig. 1, is presented. The results obtained by the proposed model are in agreement with the experimental and numerical data available from the literature (Cartie et al., 1999). In order to describe the resistance curve and crack tip location, a comparison with the behaviour of the un-pinned configuration is also presented.

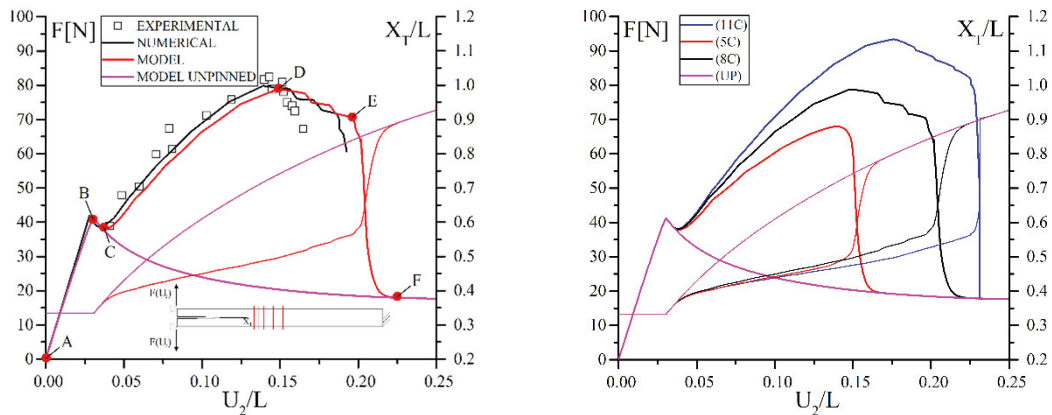


Fig. 3. (a) comparisons in terms of loading curve (F - U_2/L) and crack tip position (X_T/L) with experimental [23] and numerical [22] results; (b) influence of the number of columns of pins in terms of load-displacement curve (F - U_2/L) and crack tip position (F - U_2/L).

From point A to point C the behavior of reinforced model and un-pinned model are basically overlapped. From point C to point D the interaction with z-pin reinforced area strongly increases the resistance of the proposed model. At this stage, differences also in the prediction of the crack tip positions are observed, where the presence of the z-pin area decrease strongly the slope of curve. After that, from point D to point E, the resistance curve shows a decrease due to progressive damage of z-pin reinforced area. Finally, when the pins are completely broken, i.e. from point E to point F, the slope of crack tip position and resistance curve are strongly modified and both tend to match with ones of the un-pinned configuration.

3.1. Effect of Z-pins density

In order to verify the influence of the density of z-pins inside the reinforced area, parametric results in terms of number of columns of pins are proposed. In particular, the following idealized configurations are considered:

- Un-Pinned (UP);
- 5 number of Columns (5C);
- 8 number of Columns (8C);
- 11 number of Columns (11C).

The analyses, reported in Fig.3(b), denote that an increase of the z-pin density produces a different behavior only when the process zone reaches the z-pin region. This behavior can be explained in relations to the fact that at this stage the z-pins are include in the perfect adhesion region and thus their contribution is practically negligible. Subsequently, the maximum loads are strictly dependent from the z-pins density and the corresponding percentage increments measured with respect to the un-pinned configuration are equal to 54, 83 and 119. Moreover, the results show that the unstable evolution and thus the slope the resistance curve after the maximum loads is reached is quite influenced by the amount of the z-pins. In any cases, the curve gradually tends to the un-pinned configurations.

3.2. Effect of Z-pins reinforced area positions

In order to verify the influence of the position of z-pins reinforced area, parametric results in terms of distance between midpoint of z-pin reinforced area and the initial position of the crack tip are proposed. To this end, the following idealized configurations are considered:

- Midpoint of z-pin area is on the left of the initial position of the crack tip (L)
- Midpoint of z-pin area overlapped on the initial position of the crack tip (I)
- Midpoint of z-pin area is on the right of the initial position of the crack tip (R)

In the L or I configurations, the initial stiffness of load curve is quite dependent by the presence z-pins, since its value is quite larger than the ones observed for the remaining configurations. Moreover, after the maximum load is reached, the resistance curve decreases since the delamination process is activated. In the R configuration, the effects of the z-pins is activated only when the debonding length reaches the reinforced region. The analyses denotes that the improvement effects produced by the presence of the z-pins are partially compensated by an unstable behavior of the resistance curve after that the maximum point is reached (Fig. 4(a)).

3.3. Dynamic framework

Previous results are developed essentially in the framework of a static analysis, in which time dependent effects concerning loading rate and inertial forces are supposed to be negligible. The extension in dynamic is developed by introducing rate dependent contributions, arising from inertial effects of the structure and those involved in the debonding process, i.e. in the TLS of cohesive zone. Without loss of generality, the constitutive laws of the z-pins, are supposed to be similar to the ones utilized for the static framework. The choice of the dynamic parameters is assumed consistently with the values suggested in the literature, whereas the geometrical and material properties are identically to static case. The load process is idealized as a ramp curve, in which the velocity increases linearly until the time reaches value t_0 , after that the velocity remains constant. The value of t_0 is assumed to be proportional the first period of vibration T_1 and in the present study, a value of $t_0=0.5T_1$ was considered. The analyses are reported in Fig. 4(b), in which resistance curves for different loading rates are compared with the solution arising from the static case. Compared the static solution, in fast crack propagation, the process zone affects an enlarged damage zone with more dissipated energy, leading to larger values of the first delamination loads and some oscillations in the resistance curve. In Fig. 5(a) and (b), the crack growth is investigated also in terms of measured crack tip speed normalized on the shear wave speed (V_s) of the material, by means of time histories of delamination growth and balance energies. From these analyses, it transpires that the crack tip speeds are much larger in the initiation phase, since high strain rates are able to activate large amount of kinetic energy. Subsequently, crack tip speed shows a strongly decreasing trend when it reaches the z-pin reinforced area. Moreover, when z-pins are completely broken, the value of crack tip speed is affected by large increments. Such behavior can be explained by the energy balance reported in Fig. 5(b), which shows how the external energy is partially dissipated by the failure of the z-pins and a notable production of kinetic energy of the system is observed, since the debonding mechanisms are affected by high crack tip speeds.

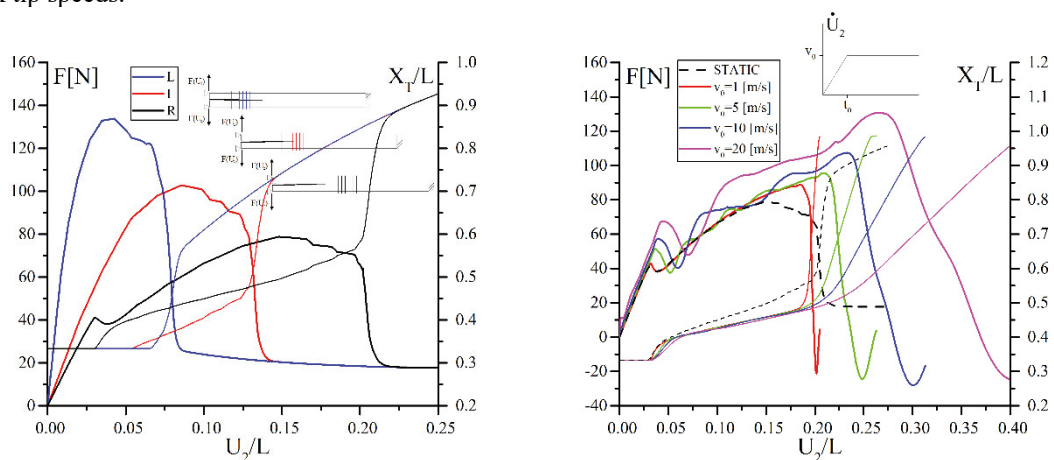


Fig. 4. (a) influence of the of the position of z-pins reinforced area; (b) influence of the loading rate in terms of load-displacement curve.

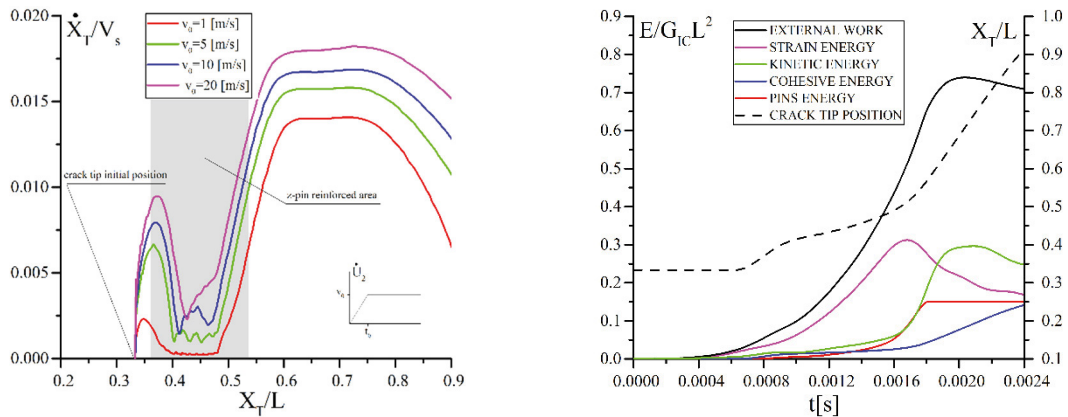


Fig. 5. (a) influence of the loading rate in terms of crack tip speed; (b) time histories of delamination growth and energies.

4. Conclusions

The proposed model is developed with the purpose to study the delamination processes of z-pinned composite laminates. Compared with existing formulations available from literature, this model presents lower computational efforts and complexities in the governing equations. In particular, the combination between CZM and ALE formulations, gives the possibility to introduce nonlinear interface elements in a small region containing the crack tip front, whereas in the remaining one, linear constrain equations are introduced to simulate perfect adhesion. In order to validate the proposed model several comparisons are proposed with experimental and numerical results. Finally, the parametric study denotes that the presence of z-pins produces notable improvements in the resistance curve. However, the pull-out mechanism introduces in the system important rate dependent effects, which strongly modify the R-curve with respect to the static case.

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