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A coupled ALE-Cohesive formulation for interfacial debonding propagation in sandwich structures

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Abstract

A numerical model to predict debonding phenomena in sandwich structures based on soft core and high performance external skins is proposed. In particular, the proposed model incorporates shear deformable beams to simulate the face sheet and a 2D elastic domain to model the core of the structure. Debonding processes is simulated by means a moving interface elements, introduced between the core and the face. The numerical interface strategy is consistent to a moving mesh technique based on Arbitrary Lagrangian–Eulerian (ALE), in which weak based moving connections are implemented by using the FE formulation. The moving mesh technique combined with a multilayer formulation ensures a reduction of the computational costs required to predict crack onset and subsequent evolution of the debonding phenomena. The accuracy of the proposed approach is verified by means comparisons with experimental and numerical results. Moreover, simulations in dynamic framework are developed to identify the influence of inertial effects produced by different typologies of core on debonding phenomena. The investigation revels the impact of mechanical properties of core on the dynamic debonding mechanisms.

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Keywords: ALE; sandwich panels; FEM; debonding.

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Nomenclature

a	initial crack length
b	length of the internal discontinuities
B	width of the specimen
g_f^k	crack growth function
G_I	mode I energy release rate
G_{II}	mode II energy release rate
G_{IC}	mode I critical strain energy release rate
G_{IIC}	mode II critical strain energy release rate
G_C	work of separation for unit area
L	length of the specimen
h^c	thickness of the core
$2\overline{\Delta}$	internal discontinuity
Δ_0	characteristic parameter of the work of separation
Ω^L	process zone on the left direction of the internal discontinuity
Ω^R	process zone on the right direction of the internal discontinuity

1. Introduction

Composites materials are widely used in several structural applications ranging from aerospace, marine (Calsson and Kaddomateas (2011)) and civil engineering (Spadea et al. (2017), Ascione et al. (2017)). In particular, sandwich structures typically consist of two thin face sheets made from stiff and strong relatively dense material such as metal or fiber composite bonded to a thick core made from low density material, namely core (Calsson and Kaddomateas (2011)). These systems are able to ensure a good resistance and a very low weight, offering a great variety of lightweight structural systems. However, these structures can be subject to macroscopic and microscopic damage phenomena. From physical and mathematical points of view there are two issues: the propagation of the fracture in the core of the structure (Morada et al. (2017)) and the delamination between the face sheet and the core (Odessa et al. (2018)). These problems have been studied by means different numerical approaches. In order to predict the angle of crack propagation in the solids, mesh-based methods like the finite element method (FEM) and the boundary element method (BEM) have shown difficulties to predict crack propagation due to extensive meshing and re-meshing procedures (Nishioka (1997)). Alternatively, Extended Finite Element Method (XFEM) are proposed to eliminate some of such difficulties, but complexities in the definition enrichment functions still exist. Others methodologies based on Meshfree Methods (MMs) have been formulated in the last decades providing alternatives to study such problems (Daxini and Prajapati (2014)). Another important failure mechanism in sandwich structures is the delamination at the skin/core interfaces. In terms of modeling, the Cohesive Zone Method (CZM) introduces interface elements at skin/core debonding lines, with effective Traction Separation Law (TSL) constitutive relationships. The CZM 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 proposed in literature, which are mainly classified as either non-potential or potential-based models (Rabinovitch (2008)). However, CZMs present computational limits, which are essentially related to the use of a dense mesh. To avoid such problems, a formulation based on CZM and moving mesh approach has been proposed (Funari et al. (2016), Funari and Lonetti (2017)), in which the multiple delaminations in layered structures, discretized by means shear deformable beams, have been investigated in both static and dynamic frameworks. In particular, this numerical approach has been extended in others works to study the produced effect by z-pins during the process of delamination (Funari et al. (2016), Funari et al. (2018)).

The main goal of this paper is to generalize the numerical implementation reported in Funari et al. (2016), making able to describe delamination phenomena in the sandwich structures. Despite existing methods, the proposed strategy is concerned to introduce a low number of computational points in the whole geometry, reducing the complexity and the computational cost. This is achieved by using a moving mesh strategy based on Arbitrary-Lagrange Eulerian (ALE) formulation, which is able to reproduce mesh movements according to the process zone motion, ensuring accuracy in the definition of the fracture variables. The outline of the paper is as follows. Section 2 presents the theoretical and numerical aspect of the implementation. In Section 3, numerical comparisons with existing formulations are proposed and a parametric study is carried out to identify the influence of inertial effects produced by different typologies of core during debonding process.

2. Theoretical Formulation and Numerical implementation

The proposed model is formulated in the framework of the sandwich structures, which consist of an internal core, modelled by using a 2D plane stress formulation whereas the skins follow a one dimensional modelling based on Timoshenko beam kinematics. According to Funari and Lonetti (2017), in order to simulate initiation and growth of interfacial defects, at the interface between skin and core a cohesive interface is introduced. This is achieved by the use of interface elements based on a moving mesh technique, which ensures an accurate description of the fracture variables and the application of cohesive interlaminar stresses in the process zone. A synoptic representation of the model is reported in Fig. 1(a).

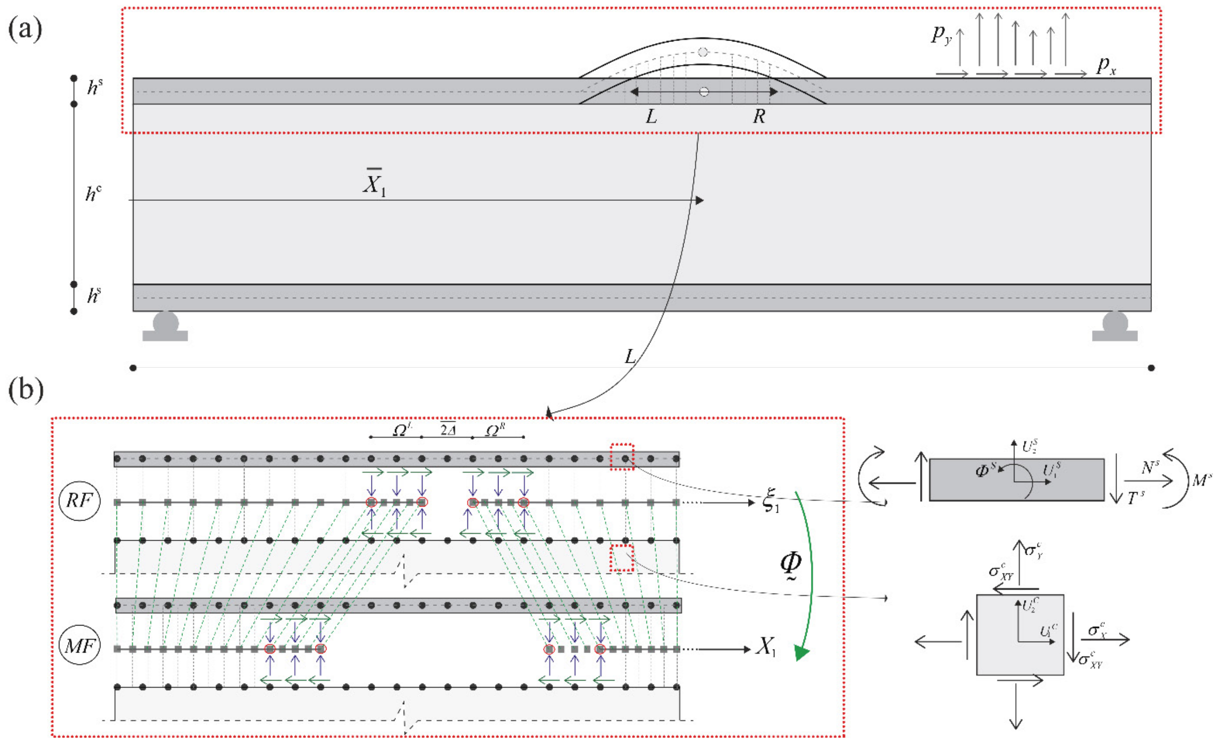

Fig. 1(a) Synoptic representation of the proposed model; (b) Moving and referential coordinate systems in ALE description.

According to Funari and Lonetti (2017), in order to simulate the crack growth, a preliminary task to be achieved is to identify the position in which the onset of interfacial mechanisms is produced and subsequently to simulate the evolution of the cracked length. Such two steps are explained separately in the following subsections.

2.1. Crack onset position

At this stage, it is only required to identify the positions in which the onset conditions are satisfied. To this end, the cohesive interfaces are introduced between each skin/core interfaces, in which the crack initiation could be potentially activated. An accurate description of the local stress distribution is not required; the model is discretized by means a relatively coarse mesh. It is worth nothing that until the crack onset condition is not satisfied, the ALE equations are inactive and the computation mesh points are expressed in the Referential Frame (RF) described by $\xi_1 - \xi_2$, which at this stage coincides with the Moving Frame (MF), described in the following subsection, i.e. $X_1 - X_2$ .The crack onset definition is described by means of a mixed crack growth, which is a function of the fracture variables, coinciding with the ratio between ERR mode components and corresponding critical values, as follows:

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

where *k* represents the generic *k-th* interface in which debonding phenomena may occur, *r* is the constant utilized to describe fracture in different material and $\left(G_{IC},G_{IIC}\right)$ are the total area under the traction separation law, whereas $\left(G_I,G_{II}\right)$ are the individual energy release rates, which could be discretized by means a bilinear nonlinear relationship. It should be noted how the proposed model is quite general to include other existing cohesive formulations based on a different TSL or stress based initiation criteria, just by modifying the analytical expressions defined in Eq.(1)

The positions, in which the cracks onset occur, are evaluated by enforcing the following condition:

$$g_f^k\left(\overline{X}_{1,i}^k\right) = 0 \quad with\ 0 \le \overline{X}_{1,i}^k \le L, i=1,N_d^k \tag{2}$$

with 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. Description of debonding process in the moving frame

It should be noted that at this step, the model presents a mesh enrichment on the interface around the defined positions by those values $\overline{X}_1^k$, which ensure accuracy in the prediction of fracture variables in proximity of the crack onset positions. Starting from the onset coordinate $\overline{X}_1^k$, a small geometric discontinuity with length equal to $\overline{2\Delta}$ is introduced in the numerical model, producing two potentially independent debonding mechanisms that could evolve along left and right directions (Fig.1(b)). ALE strategy has been implemented in the interface region to accurate describe the evolution of debonding phenomena (Bruno et al. (2009), Funari et. al (2016)). In particular, each interface is modified by the ALE equations, making able to reproduce the moving traction forces acting at the skin/core interfaces. From the mathematical point of view, the relationship between RF and MF is guaranteed by the introduction of a mapping operator Φ (Fig.1(b)), which relies a particle in a RF to the one in MF, as follows:

$$\underset{\sim}{X} = \Phi\left(\underset{\sim}{\xi},t\right) \quad with\ \Phi : RF \rightarrow MF \tag{3}$$

In particular, the prescribed motion is expressed in terms of the following Laplace-based equations developed for Static (S) or Dynamic (D) frameworks:

$$\Delta X_{1,\xi\xi}^{j} = \frac{\partial^2 \Phi^j(\xi,t)}{\partial \xi_1^{\,2}} = 0 \qquad (S) \qquad \Delta \dot{X}_{1,\xi\xi}^{j} = \frac{\partial^3 \Phi^j(\xi,t)}{\partial t \partial \xi_1^{\,2}} = 0 \qquad (D) \tag{4}$$

where j, with j=L, R, represents the index referred to the Left (L) or Right (R) process zones, whereas ΔX_1^j correspond to the mesh displacement and it is evaluated by means the follow equation (Lonetti (2010)):

$$\Delta X_1^j = X_1^j(t) - \xi_1^j \tag{5}$$

The prescribed mesh motion introduces a rigid displacement of the process zone, which is identified on the basis of internal lengths for the left and right crack directions, namely Ω^L or Ω^R (Fig. 1(b)). From the geometrical point of view, the process zone is assumed to be moved rigidly by using of the ALE strategy (Funari et al. (2016)). Such task is performed by means a simple procedure, which consists, at first, to predict the values of the fracture function at their extremities and, subsequently by enforcing that during the crack growth a null value of the fracture is achieved. Therefore, by using a linear approximation function along the debonding region, the current nominal crack tip displacement can be expressed by means the following relationships:

$$\overline{\Delta X_1}^{L,R} = 0 \quad g_f^k \le 0, \;\; \overline{\Delta X_1}^{L,R} = \frac{g_f^k\left(\overline{X_1}^{L,R}\right)}{g_f^k\left(\overline{X_1}^{L,R}\right) \pm g_f^k\left(\overline{X_1}^{L,R} \pm \Omega^{L,R}\right)} \Omega^{L,R} \quad g_f^k > 0 \tag{6}$$

Governing equations are formulated by means a numerical formulation based on the FE methods. The proposed model takes the form of a set of nonlinear differential equations, whose solution is obtained by using a customized FE subroutine in the framework of COMSOL Multiphysics software, by means of scripting capabilities of MATLAB® language (COMSOL (2014)). The proposed procedure is quite general and can be solved in both static on dynamic frameworks, taking into account the time dependent effects produced by the inertial characteristics of the structure and the boundary motion involved by debonding phenomena. Since the governing equations are essentially nonlinear, an incremental-iterative procedure has been adopted to evaluate the current solution.

3. Results

In this section, the proposed model is verified by means of several comparisons with numerical and experimental data. The first step in the validation scheme is developed with the purpose to analyze the consistency of the proposed formulation with respect to classical DCB (Fig. 2(a)) and MMB (Fig.2(b)) loading schemes. In particular, according to standard test methods, the static behavior of interfacial crack propagation at the upper interface between face-sheet and core is investigated. The main aim of the comparison with the numerical (Odessa et al. (2017)) and experimental (Carlsson and Kardomateas (2011)) data is to validate the proposed model and to examine its ability to describe the debonding failure mechanism in sandwich panels. Subsequently, the dynamic behavior will be studied to identify the influence of inertial effects, produced by different level of the loading rate and by different core typologies.

3.1. DCB test

At first, the analyses are developed with reference to loading schemes based on classical DBC test. The loading, the boundary conditions and the geometry are illustrated in Fig. 2(a). whereas, according to data recovered in (Odessa et al. (2017)), mechanical properties assumed for the skins, core and interfaces, are summarized in Tab.1.

In Fig. 3(a) the relationship between resistance, applied displacement and nominal crack tip position, for two different core thickness configurations, i.e. h^c=15-20 mm, are reported. The results obtained by the proposed model are in agreement with the experimental (Prasad and Carlosson (1994)) and numerical (Odessa et. Al (2017)) results. It is that worth noting that the results show how an increment in the core thickness does not produce significant variations in the loading curve.

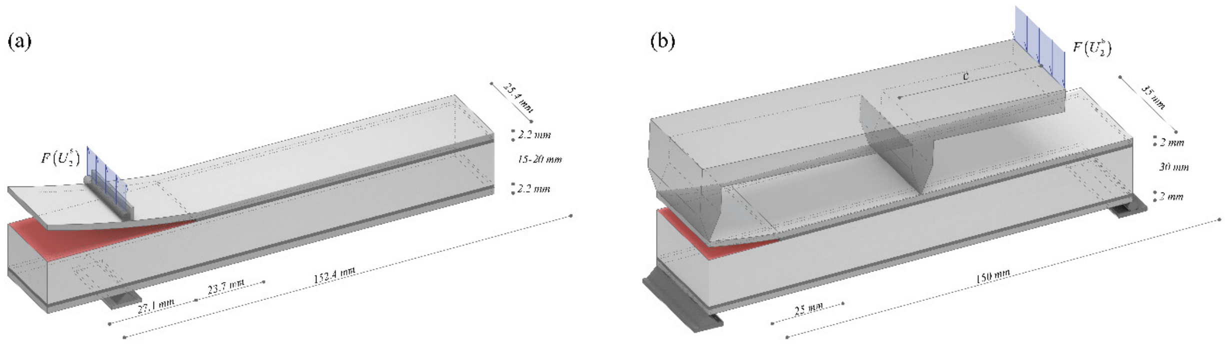

Fig. 2(a) DCB scheme; (b) MMB scheme.

Table 1. DCB test: mechanical and interface properties.

Face – sheet aluminum	**E_{11}^{s} [MPa]**	**G_{12}^{s} [MPa]**	**ν^{s}**	**ρ^{s} [Kg/mc]**
	$70\ 10^3$	$26\ 10^3$	0.33	2700
Core – PMI AIRES R 90.400	**E_{1}^{c} [MPa]**	**G_{12}^{c} [MPa]**	**ν^{s}**	**ρ^{c} [Kg/mc]**
	420	220	0.25	400
Interface properties	**G_c [N mm^{-1}]**	**Δ_0 [mm]**	-	-
	0.550	0.12	-	-

3.2. MMB test

In this subsection the analyses are referred to loading scheme based on classical MMB test, as shown in Fig. 2(b). The values of mechanical and interface properties assumed for the structure are reported in Tab. 2. In Fig. 3(b) the calibration procedure of the cohesive model is performed varying the value of the mixed mode ratio (changing *c* length). The proposed model shown a good agreement with the experimental data (Carlosson and Kardomateas (2011), Quispitupa et al. (2009)).

Previous analyses, developed essentially in static, are extended in a dynamic framework. The main aims of the results are to investigate the influence of the loading rate and the inertial effects produced by different typologies of core. The loading history is assumed to be governed by an applied velocity with ramp curve with a constant speed (v_0) at the time t_0, which is assumed to be proportional to the first period of vibration (T_1) of the structure ($t_0=0.5T_1$). At first, in order to verify the influence of the loading rate, parametric results in terms of v_0 are proposed. In particular, the following value of v_0 are considered:

- $v_0=1ms^{-1}$;
- $v_0=5ms^{-1}$;
- $v_0=10ms^{-1}$.

Table 2. MMB test: mechanical and interface properties.

Face – sheet glass/polyester	**E_{11}^{s} [MPa]**	**G_{12}^{s} [MPa]**	**ν^{s}**	**ρ^{s} [Kg/mc]**
	$16.4\ 10^3$	$2.7\ 10^3$	0.17	1500
Core – DIVINYCELL H100	**E_{1}^{c} [MPa]**	**G_{12}^{c} [MPa]**	**ν^{s}**	**ρ^{c} [Kg/mc]**
	135	35	0.32	100
Interface properties	**G_c [N mm^{-1}]**	**Δ_0 [mm]**	-	-
	0.800	0.10	-	-

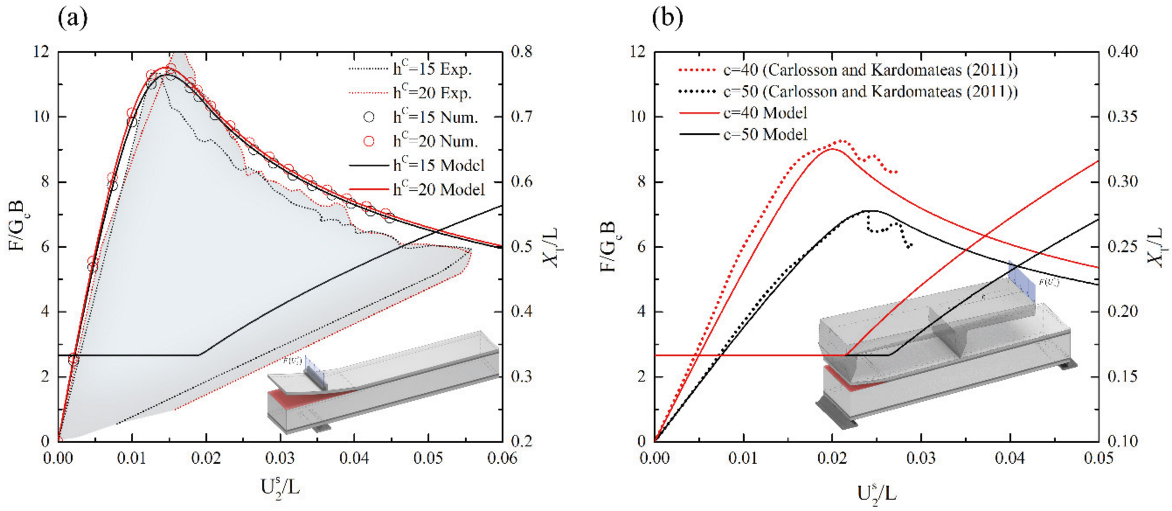

Fig. 3(a) DCB test: comparisons in terms of loading curve with experimental (Prasad and Carlosson (1994)) and numerical data (Odessa et al. (2017)); (b) MMB test: comparisons in terms of loading curve with experimental data (Carlosson and Kardomateas (2011)).

Table 3. Mechanical properties DIVINYCELL H.

	E^s_{11} [MPa]	G^s_{12} [MPa]	ρ^s [Kg/mc]
DIVINYCELL H35	40	12	38
DIVINYCELL H100	135	35	100
DIVINYCELL H250	400	97	250

In Fig. 4(a), results in terms of resistance curve are reported. At low value of v_0, static and dynamic solutions are overlapped. Contrarily, when the value of v_0 increases, the resistance curve denotes an increment of the peak load with an oscillating behavior. In Fig. 4(b), results are investigated also in terms of measured nominal crack tip speed. From these analyses, it transpires that the crack speeds are much larger in the initiation phase. Subsequently, during the process of delamination, the crack speed tends to decrease.

Finally, the influence of the mechanical properties of the core is investigated. The data concerning the core typology are reported in Tab. 3. The loading rate is described by the same ramp curve used to the results presented above, in which a value of v_0 equal to 10 [ms^{-1}] is adopted.

In Fig. 5(a), the resistance curves are not influenced in terms of peak load, whereas more marked differences in terms of initial stiffness are observed. In particular, the specimen characterized by the use of a heavier core present smaller increment in terms stiffness and peak load. Instead, the use of a lighter core can guarantee important capacity in terms of deformability during the crack propagation. Finally, in Fig. 5(b), an investigation in terms of crack speed is presented. The results show that an increment in the core weight does not produce relevant amplifications of the nominal crack speed.

4. Conclusions

The proposed model is developed with the purpose to study the behavior of sandwich structures affected by debonding phenomena. The numerical model is inspired by the previous works of the authors, performed in the framework of the layered structures and here generalized to sandwich structures.

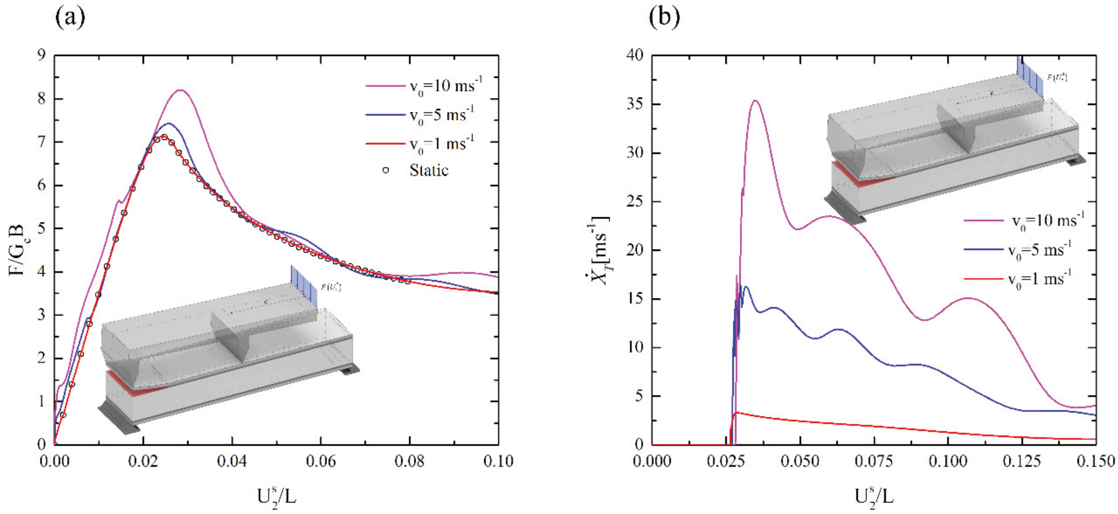

Fig. 4(a) MMB test: influence of the loading rate in terms of loading-displacement curve; (b) MMB scheme: influence of the loading rate in terms of nominal crack tip speed.

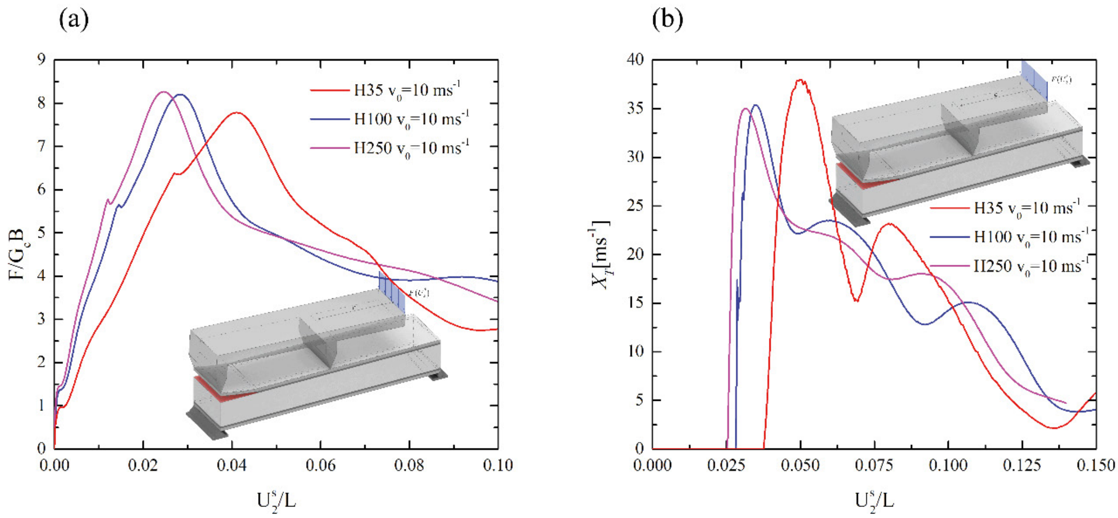

Fig. 5(a) MMB test: influence of the core typology in terms of loading-displacement curve; (b) MMB test: influence of the core typology in terms of nominal crack tip speed.

In this work, the numerical model is based on a 2D plane stress formulation to simulate the internal core, whereas the face-sheets follow a one dimensional model based on Timoshenko beam kinematics. In order to describe the delamination process, the proposed approach combines ALE formulation with a CZM. Compared to existing formulations available i literature, this model presents lower computational 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. Comparisons with experimental and numerical results are proposed to verify the consistency of the proposed modeling.

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