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# Numerical study for the structural analysis of composite laminates subjected to low velocity impact

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ABSTRACT

The paper deals with structural behaviour of laminated composite plates under low velocity impact loading conditions. The aim of the work is to develop numerical finite element models and simulation techniques to be implemented in a numerical procedure, which is aimed to improve designer forecasting capabilities of damaging resistance in composite structures.

On the base of advanced material models and of selected failure criteria, the proposed numerical techniques can describe the damage initiation and propagation of impact damages in composite structures.

A global/local finite element modeling approach has been proposed, in order to be able to develop explicit finite element analysis of the impact event, including damage initiation and propagation of both interlaminar and intralaminar damages. The same model has been analysed under quasi static compression conditions by taking into account, in a single explicit finite element analysis, both the impact and the after impact damages.

For validation purpose, numerical results have been compared with data from two sessions of experimental impact tests, followed by compression after impact tests; the considered impact energy values are 50 J and 100 J respectively.



## 1. Introduction

The impact damage is an event that frequently affects the aeronautical structures. Typical sources of impact are tools falling during manufacturing or maintenance operations, hail, debris on the track, bird collision, etc.

Impact damages heavily influence the mechanical properties of composite material and then the residual strength of composite structure. Typical composite damaging modes, such as matrix breakage, fiber failure and delamination [1–5], are very difficult to take into account during the design process and barely detectable during maintenance inspections. For these reasons, critical design aspects of composite structures, such as damaging under low [6] and high [7] velocity impacts, notch sensitivity and environmental conditions imply application of conservative safety factors to the ultimate load values of composite components. In particular, in order to take into account low velocity impact damages and notch sensitivity effects the ultimate load value is generally reduced by 30%. This safety factor, combined with those ordinarily applied during the design phase, reduces altogether the ultimate load design value of composite structures by about 65–70%, with a significant increasing in weight and dimensions of the whole structure. The aim of this work is studying and better understanding the growing mechanisms of low velocity impact damages in order to try to reduce the correlated design safety factor under a damage tolerant design philosophy.

Nowadays, from an experimental point of view, the best practice to detect a damage from low velocity impact is the non destructive ultrasound technique, which can appear a slow and expensive method, as well as technologically complex to apply on very large components.

Ultrasound technique has been used within this work to detect impact damages on standard coupon tested under ASTM D7136 (American Standard Test Method for Measuring the Damage Resistance of a Fiber –Reinforced Polymer Matrix Composite to a Drop Weight Impact) requirements and by considering impact energy values of 50 J and 100 J for two different experimental sessions.

From a numerical point of view, a detailed finite element model of the coupon has been created by considering a global/local approach and both intralaminar and interlaminar failure criteria have been modeled by using algorithms implemented in the finite

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element code ABAQUS Explicit® [8]; also different kind of contact features and algorithms were investigated evaluating their efficiency in order to reach a stable numerical convergence [9–11]. Failure criteria main parameter values have been chosen by standard longitudinal and flexural tests on plate, ENF and DCB specimens; then, other specific parameters have been calibrated and numerically tuned by considering fracture energy balance criteria. Experimental tests have been developed at the Italian Aerospace Research Centre (CIRA) laboratories in Capua, Italy.

The global/local approach employed in FE modeling allows reducing the average mesh density, by considering in plane and through the thickness relatively coarse mesh for the global part of the model and finer mesh for the local one, including impacted area; in the local part of the model the composite material has been modeled layer by layer. The use of this modeling approach is mandatory when using the proposed simulation procedure, which is very CPU time consuming; in fact, the model has been analysed under impact and static compression after impact (CAI) loading conditions [12–14] by two steps in a single explicit finite element analysis. Good results have been achieved for both the loading conditions. It is underlined that the proposed procedure allows performing numerical CAI simulations by taking into account the effective impact damage distribution.

## 2. Test description

Nowadays, the evaluation of allowable strains for composite structures is an experimental task in the design process [15]; an impact test on standard plate coupons and a quasi static compression test on the same damaged coupon is the usual procedure to investigate on the residual strength of impacted components.

Requirements prescribed by both ASTM D7136 and ASTM D7137 (Standard Test method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates) govern the tests [16–18].

The in plane dimensions of the coupon are 100 mm × 150 mm, with a composite laminate thickness of 4.3 mm (24 plies, each one 0.179 mm thick, with a stacking sequence $[(45, -45, 0, 90)_3]_{sym}$); lamina material proprieties are shown in Table 1.

A drop tower impact-test device has been used (CEAST Fractovis); the drop mass, with a smooth hemispherical striker tip with a diameter of 19 mm, is 7.51 kg and the impact speed value is 3.65 m/s, for the 50 J impact energy tests, and 5.16 m/s, for the 100 J impact energy tests. The quasi static compression load rate is equal to 0.005 mm/ms.

## 3. FE model description

A global–local approach [6,8,19–21] has been used to model the coupon: a refined mesh in the local impacted area (2.5 mm element average size) and a coarser one in the rest of the model (5 mm element average size) have been used. This modeling approach allows reducing the required CPU time. Moreover, in the local area, each lamina of composite material has been modeled with one layer of plane finite elements; between each pair of laminae, cohesive elements have been placed to simulate stiffness, strength and fracture toughness of the interlaminar interface, with the aim to capture the delamination damage onset and propagation [22–25]. Since the composite laminate is composed by 24 plies, 23 layers of cohesive elements have been used, where the thickness of each cohesive element is 0.001 mm.

The constitutive model of cohesive elements is based on a bilinear traction separation law, relating the interlaminar stress ($\sigma$) to the separation displacement ($\delta$), between the nodes at the interlaminar interface (Fig. 1). By increasing the separation displacement, the tractions across the interface increase linearly, with a prefixed slope (penalty stiffness $k_p$), up to reach a maximum value ($\sigma_c$) in correspondence of the effective displacement at the damage initiation ($\delta_{0i}$); then, it decreases linearly up to vanish if the complete decohesion at the interlaminar interface occurs, that is $\delta_{max}$ value is reached.

To understand the meaning of penalty stiffness, it can be useful to introduce the ratio between $\delta_{0i}$ and $\delta_{max}$. In fact, given $\sigma_c$ and $\delta_{max}$ values, if such ratio is equals to 1, it means that the damage evolution occurs along a vertical path with a very brittle failure type. If the ratio is lower than 1, the failure develops smoothly.

In other words, as the ratio changes, also the penalty stiffness $k_p$ changes; then, the meaning of this parameter turn out to be the stiffness softening of the interlaminar interface.

In particular, the value of the penalty stiffness can be calculated using the relation (8) showed in the following.

In particular, with reference to Fig. 1, the area under the bilinear softening law, $E_{num}$, is given by the relation (1):

$$E_{num} = E_{exp} = \frac{1}{2}\sigma_c\delta_{max}, \quad (1)$$

where $E_{exp}$ is the experimental energy release rate at failure ($G_{I,II,IIIC}$).As shown in Fig. 1:

$$\sigma_c = K_p\delta_{0i}; \quad (2)$$

then, it is:

$$E_{exp} = E_{num} = \frac{1}{2}K_p\delta_{0i}\delta_{max}. \quad (3)$$

Dividing and multiplying for $\delta_{max}$, we have:

$$E_{exp} = E_{num} = \frac{1}{2}K_p\frac{\delta_{0i}}{\delta_{max}}\delta^2_{max} = \frac{1}{2}K_p\delta_{ratio}\delta^2_{max}, \quad (4)$$

where

$$\delta_{ratio} = \frac{\delta_i}{\delta_{max}}; \quad (5)$$

By relation (4):

$$K_p = \frac{2E_{exp}}{\delta_{ratio}(\delta^2_{max})}, \quad (6)$$

and from relation (1):

**Table 1**
Unidirectional lamina material proprieties.

| | | | |
|---|---|---|---|
| Longitudinal Young modulus $E_{11}$ | 156 (GPa) | Longitudinal tensile strength $X_t$ | 2500 (MPa) |
| Transverse Young modulus $E_{22}$ | 8.35 (GPa) | Longitudinal compr. strength Xc | 1400 (MPa) |
| In plane shear modulus $G_{12} = G_{13}$ | 4.2 (GPa) | Transverse tensile strength Yt = Zt | 75 (MPa) |
| In plane shear modulus $G_{23}$ | 2.52 (GPa) | Transverse compr. strength Yc = Zc | 250 (MPa) |
| Poisson ratio $\nu_{12} = \nu_{13}$ | 0.33 | Shear strength $S_{12} = S_{13}$ | 95 (MPa) |
| Poisson ratio $\nu_{23}$ | 0.55 | Shear strength $S_{23}$ | 108 (MPa) |
| Critical ERR-MODE $G_{IC}$ | 288 ($Jm^{-2}$) | Critical ERR-MODE II-III $G_{II-IIIc}$ | 610 ($Jm^{-2}$) |