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PREDICTING THE STRUCTURAL BEHAVIOUR OF COMPOSITE LAMINATES SUBJECTED TO IMPACT LOADING

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Abstract. *This paper presents two in-plane progressive failure models for the prediction of the structural behaviour of composite laminates subjected to impact loading. The formulation for the first model uses a set a failure criteria to detect damage initiation and a time-step based degradation scheme to predict damage progression. On the other hand the formulation for the second model is based on the Continuum Damage Mechanics (CDM) approach in which cracks are assumed to be smeared over a Representative Volume Element (RVE) of the material. The smeared cracking formulation proposed in this work combines fracture mechanics and damage mechanics approaches in a unified way enabling damage prediction within energy based framework. The CDM model also incorporates shear non-linearities, irreversible strains and strain rate effects for shear dominated failure modes. Both models were implemented as user defined materials into the VUMAT Fortran subroutine available in ABAQUS FE code.*
Impact tests in different energy levels were carried out to validate the models. The experiments were conducted using an in-house drop test tower apparatus available in the LEICA (Laboratório de Estruturas Inteligentes e Compósitos Avançados) at ITA. The tests were performed in accordance with the Boeing Specification Support standard test.
A very good correlation in terms of peak load, impact duration, membrane and bending strains was found between experimental results and numerical predictions obtained using the proposed CDM model.

Keywords*: composites, damage mechanics, impact, finite elements*

1. INTRODUCTION

Composite laminates have been widely used in advanced structural engineering applications such as airplane wings, helicopter blades and turbine blades as well as many others in the aerospace, mechanical, and automotive industries. They play a significant role in the design when the weight and strength are of primary consideration. However, the poor properties in the through thickness direction make composite structures particularly made of carbon fiber reinforced plastic (CFRP) susceptible to low velocity impact damage. The damage resistance and damage tolerance of composite laminate structures can also be effectively and efficiently enhanced by changing the lay-up parameters. A large number of investigators has addressed the problem of impact damage in composite laminates (Abrate, 1998) and a several failure criteria have been developed to predict the response of those structures (Hou, *et al.,* 2000, Huang and Lee 2003, Kelly and Hallstrom, 2005).

This paper presents a numerical and experimental investigation on the impact induced damage in composite laminates. For this purpose two bidimensional numerical models were developed. Both models use a set of failure criteria to predict damage initiation. The formulation for the first model incorporates a time step degradation scheme to predict damage extent whilst the formulation for the second model is based on the Continuum Damage Mechanics approach enabling the control of the energy dissipation by using a smeared cracking formulation (Bazant, 1983). The proposed formulation for the second model is based on the previous work developed by Donadon *et al*. (2008).
The numerical results obtained using both models are compared to the experimental data. The tests were carried out in accordance with the Boeing Specification Support standard test using an in-house drop test tower apparatus available in the LEICA (Laboratório de Estruturas Inteligentes e Compósitos Avançados) at ITA.

2. FAILURE MODELS FORMULATIONS

2.1. Progressive failure model based on a time-step degradation procedure

This failure model was developed for plane stress elements and it uses the failure criteria proposed by Chang and Chang (1984) to detect tensile matrix cracking, tensile fibre breakage and fibre/matrix debonding in shear. Matrix cracking in compression is predicted using the criterion proposed by Hashin (1980) whilst the maximum stress criterion (Jones, 1999) is used to predict fibre breakage in compression.

The model requires the six material parameters listed below,

- X_t, longitudinal tensile strength
- X_c, longitudinal compressive strength

- Y_t , transverse tensile strength
- Y_c , transverse compressive strength
- S_{12} , shear strength
- α , nonlinear shear stress parameter.

The criteria for fiber and matrix failure due to tensile loads are based on the Yamada-Sun criteria (Chang *et al.*, 1984). To evaluate damage initiation, is used a index failure given by,

$$e_\beta^t = \left(\frac{\sigma_i}{\mathrm{B}_i}\right)^2 + \frac{\dfrac{\tau_{12}^2}{2G_{12}} + \dfrac{3}{4}\alpha\tau_{12}^4}{\dfrac{S_{12}^2}{2G_{12}} + \dfrac{3}{4}\alpha S_{12}^4} \geq 1 \tag{1}$$

where β relates to the local lamina direction ("*f*" for fiber direction and "*m*" for matrix direction). B_i relates to the local lamina strength and i relates to the local material coordinate system (1 or 2). Thus, the failure index associated with fiber failure in tension is given by,

$$e_f^t = \left(\frac{\sigma_1}{X_t}\right)^2 + \frac{\dfrac{\tau_{12}^2}{2G_{12}} + \dfrac{3}{4}\alpha\tau_{12}^4}{\dfrac{S_{12}^2}{2G_{12}} + \dfrac{3}{4}\alpha S_{12}^4} \geq 1 \tag{2}$$

Similarly the failure index for matrix cracking in tension reads,

$$e_m^t = \left(\frac{\sigma_2}{Y_t}\right)^2 + \frac{\dfrac{\tau_{12}^2}{2G_{12}} + \dfrac{3}{4}\alpha\tau_{12}^4}{\dfrac{S_{12}^2}{2G_{12}} + \dfrac{3}{4}\alpha S_{12}^4} \geq 1 \tag{3}$$

The failure index for fiber failure in compression is given by,

$$e_f^c = \frac{|\sigma_1|}{X_c} \geq 1 \tag{4}$$

and for matrix cracking in compression is written as follows (Hashin, 1980),

$$e_m^c = \left(\frac{\sigma_2}{S_{12}}\right)^2 + \left[\left(\frac{S_C^T}{2S_{12}}\right)^2 - 1\right]\frac{\sigma_2}{S_C^T} + \frac{\dfrac{\tau_{12}^2}{2G_{12}} + \dfrac{3}{4}\alpha\tau_{12}^4}{\dfrac{S_{12}^2}{2G_{12}} + \dfrac{3}{4}\alpha S_{12}^4} \geq 1 \tag{5}$$

After detecting damage initiation, internal damage variables $d_{ij}^r \in$ [0,1] are calculated. The subscripts *i* and *j* relate to the local material coordinate system, where *i*, *j* =1 indicates fiber breakage and *i*, *j* =2 indicates matrix cracking. The superscript *r* indicates the failure mode, where *r* = *t* and *r* = *c* indicates failure in tension and compression, respectively. The degraded stresses are taken to zero in one hundred time steps in order to avoid numerical instabilities during the integration process of the nonlinear equilibrium equations. For shell elements, the degraded stresses are given by,

$$\begin{Bmatrix}\sigma_1\\\sigma_2\\\tau_{12}\end{Bmatrix}^d=\begin{bmatrix}d_{11}^t d_{11}^c & 0 & 0\\ 0 & d_{11}^t d_{11}^c d_{22}^t d_{22}^c & 0\\ 0 & 0 & d_{11}^t d_{11}^c d_{22}^t\end{bmatrix}\begin{Bmatrix}\sigma_1\\\sigma_2\\\tau_{12}\end{Bmatrix}^{el} \quad (6)$$

2.2. Progressive failure model based on energy

The criteria to detect damage initiation for the energy failure model are all based on the maximum stress criteria (Jones, 1999). To evaluate damage initiation, the failure indexes associated with the in plane failure modes are presented below,

Tensile fiber failure mode:

$$e_{fiber}^t=\frac{\sigma_1}{X_t}\geq 1 \quad (7)$$

Compressive fiber failure mode:

$$e_{fiber}^c=\frac{|\sigma_1|}{X_c}\geq 1 \quad (8)$$

Tensile matrix cracking mode:

$$e_{matrix}^t=\frac{\sigma_2}{Y_t}\geq 1 \quad (9)$$

Compressive matrix cracking mode:

$$e_{matrix}^c=\frac{|\sigma_2|}{Y_c}\geq 1 \quad (10)$$

In-plane shear failure mode:

$$e_{matrix}^s=\frac{|\tau_{12}|}{S_{12}}\geq 1 \quad (11)$$

2.2.1. Damage growth

The general expression for the damage evolution laws used in this model is based on the work proposed by Donadon *et al*. (2008) and is given by,

$$d_{ij}(\lambda_1^\beta,\lambda_2^\beta)=\lambda_1^\beta+\lambda_2^\beta-\lambda_1^\beta\lambda_2^\beta \quad (12)$$

where β relates to the local material coordinate system (β =*f*, for damage in the fiber direction and β =*m*, for damage in the matrix direction). These laws are explicitly written as follows for each failure mode,

Damage evolution law for fiber failure:

$$d_{11}(\lambda_1^f,\lambda_2^f)=\lambda_1^f+\lambda_2^f-\lambda_1^f\lambda_2^f \quad (13)$$

with

$$\lambda_1^f=\left(\frac{2\bar{G}_f^t}{2\bar{G}_f^t-X_t l^*\varepsilon_{1,0}^t}\right)\left(\frac{\varepsilon_1^t-\varepsilon_{1,0}^t}{\varepsilon_1^t}\right) \quad (14)$$

$$\lambda_2^f = \left(\frac{2\overline{G}_f^c}{2\overline{G}_f^c - X_c l^* \varepsilon_{1,0}^c} \right) \left(\frac{\varepsilon_1^c - \varepsilon_{1,0}^c}{\varepsilon_1^c} \right) \tag{15}$$

In a similar way, the damage evolution law for matrix cracking is given by,

$$d_{22}(\lambda_1^m, \lambda_2^m) = \lambda_1^m + \lambda_2^m - \lambda_1^m \lambda_2^m \tag{16}$$

with,

$$\lambda_1^m = \left(\frac{2\overline{G}_m^t}{2\overline{G}_m^t - Y_t l^* \varepsilon_{2,0}^t} \right) \left(\frac{\varepsilon_2^t - \varepsilon_{2,0}^t}{\varepsilon_2^t} \right) \tag{17}$$

$$\lambda_2^m = \left(\frac{2\overline{G}_m^c}{2\overline{G}_m^c - Y_c l^* \varepsilon_{2,0}^c} \right) \left(\frac{\varepsilon_2^c - \varepsilon_{2,0}^c}{\varepsilon_2^c} \right) \tag{18}$$

where the functions λ_1^f, λ_2^f, λ_1^m and λ_2^m assume values within the interval (0,1). $\overline{G}_f^t$ and $\overline{G}_f^c$ are the intralaminar fracture toughnesses associated with fibre breakage in tension and compression, respectively. The parameters $\overline{G}_m^t$ and $\overline{G}_m^c$ are the intralaminar fracture toughnesses associated with matrix cracking in tension and compression, respectively. The maximum strains prior to catastrophic failure in tension and compression in the fibre direction are defined as $\varepsilon_{1,0}^t$, $\varepsilon_{1,0}^c$ respectively.

The in-plane damage evolution law is given by,

$$d_{12}(\gamma_{12}) = \frac{\gamma_{12,f}[2(\gamma_{12} - \gamma_{12,0}^{in}) - \gamma_{12,f}]}{(\gamma_{12,f} + \gamma_{12,0}^{in} - \gamma_{12})(\gamma_{12} - \gamma_{12,0}^{in})} \tag{19}$$

with

$$\gamma_{12,f} = \frac{2\overline{G}_S}{S_{12} l^*} \tag{20}$$

where $\gamma_{12,0}^{in}$ is the inelastic strain at failure and $\overline{G}_S$ is the in-plane shear intralaminar fracture toughness. The characteristic lengths l^* presented in the equations above relate the size of the process zone to the size of the finite element mesh. Details on the derivation of the characteristic lengths can be found in Donadon *et al.* (2008).

For shell elements the degraded stresses for the energy based failure model is written as follows,

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix}^d = \begin{bmatrix} 1 - d_{11}(\lambda_1^f, \lambda_2^f) & 0 & 0 \\ 0 & (1 - d_{11}(\lambda_1^f, \lambda_2^f))(1 - d_{22}(\lambda_1^m, \lambda_2^m)) & 0 \\ 0 & 0 & 1 - d_{12}(\gamma_{12}) \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix}^{el} \tag{21}$$

3. FINITE ELEMENT MODEL

The test coupons were modeled using ABAQUS FE code. The finite element used in the simulations consists of a 4-node-quadrilateral shell element available in ABAQUS. Detailed description on the finite element formulation may be found in (Abaqus, 2004). A frictionless hard contact based on the penalty formulation was used to simulate the interaction between the plate and the striker. The simulations were performed using the Dynamic Explicit solver available in ABAQUS (Abaqus, 2004). A lumped mass with the same weight value of the real striker (1.5314 kg) was assigned to the central node of the striker mesh. A velocity field was also applied to the striker. For the numerical simulations the plate was assumed to be clamped on the four edges, as shown in Fig. 1. The plate has dimensions of 150 x 100 mm with quasi-isotropic lay-ups.

A uniform square mesh was selected for the impact simulations to preserve an unbiased damage propagation path. In order to validate the model, the numerical predictions were compared to experimental data available in the open literature (Davies, 1995). After validating the model, numerical analyses were carried out for each impact velocity measured during the experimental impact tests.

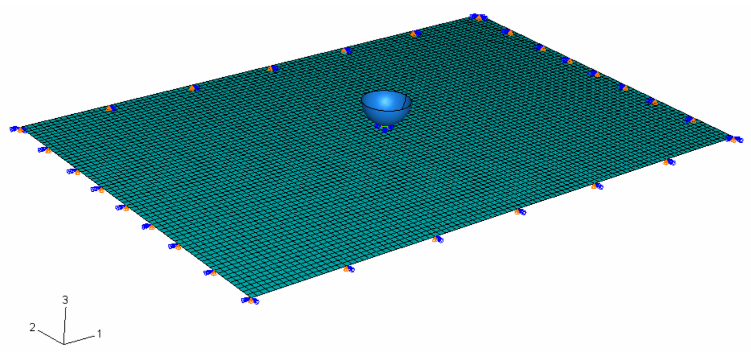
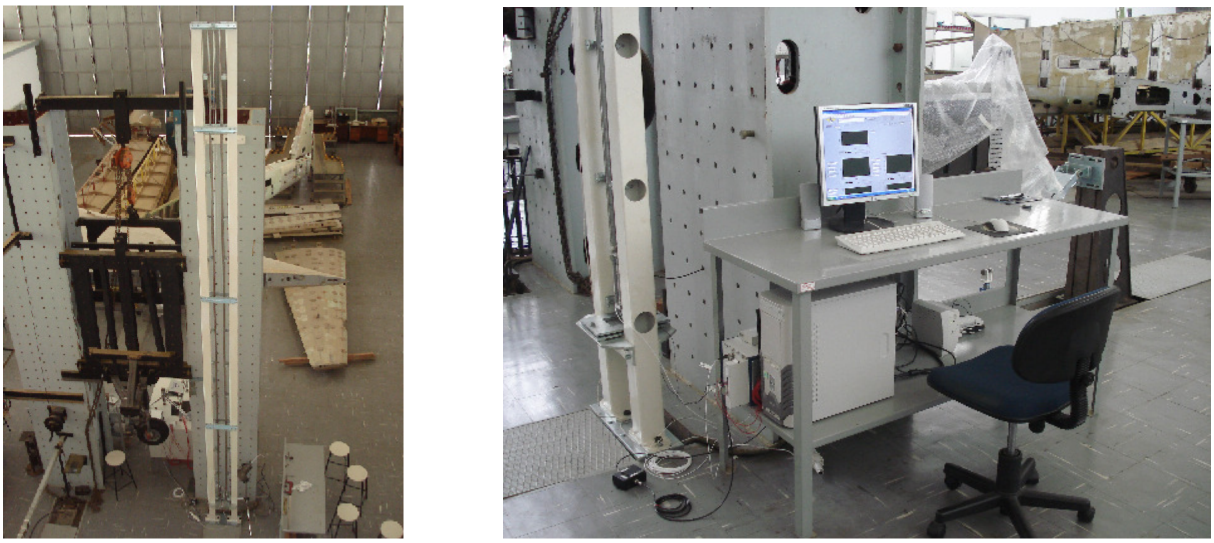


Figure 1. Mesh and boundary conditions of the numerical impact model

4. IMPACT TESTS

A Drop weight impact test tower was used to investigate the structural behavior of the composite laminates subjected to impact loads. The 7 meter tower was designed by the researchers from LEICA at ITA. The tower specifications were in accordance with the Boeing Specification Support Standard Test (1976). The test apparatus allows conducting impact testing at low/medium velocities (Fig. 2.a).

The impact force was measured using a piezoelectric load cell attached to a 12.5 mm diameter hemispherical steel impactor. A photosensor was used as a trigger and also to measure the impact velocities. The velocity and displacement time histories were obtained from successive integrations of the impact force time history. Two strain gages were mounted on the top and bottom surfaces of the laminate composite (See Fig. 3) to measure the bending and membrane strains during the impact event. The data acquisition system consists of a 4-slot chassis NI SCXI-1000 signal conditioner supplied by National Instruments. This system is capable of acquiring data at rates up to 333 kS/s for each DAQ device. The software used to manage the data was LabView 8.2. This software has a large number of programs and subroutines named VI (short for Virtual Instruments). It allows the user to implement a customized routine. A *VI* called “Impact Test” was implemented to acquire and exhibit the photosensor, load cell and strain-gages signals. The test setup together with the data acquisition system is shown in Fig. 2.b.



(a) (b)

Figura 2. (a):Drop weight impact test tower, (b): Computer and data acquisition system used to perform the impact tests

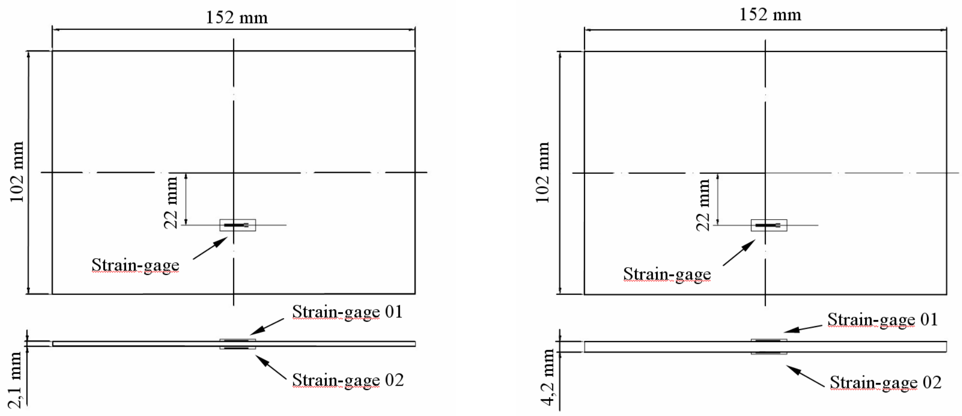


Figure 3. Dimension of the laminate 01 and position of the strain gages (a) Dimension of the laminate 02 and position of the strain gages (b)

Table 1. Material properties

Property	Symbol	Value
Elastic modulus in fiber direction	E_1	60.8 GPa
Elastic modulus in transverse direction	E_2	58.25 GPa
Poisson's ratio	ν_{12}	0,07
Shear modulus in 1-2 plane	G_{12}	4.55 GPa
Tensile strength in fiber direction	X_t	621 MPa
Tensile fracture toughness in fiber direction(1)	$\overline{G}_f^t$	100 kJ/m^2
Compression strength in fiber direction	X_c	760 MPa
Compression fracture toughness in fiber direction(1)	$\overline{G}_f^c$	25 kJ/m^2
Compression strength in transverse direction	Y_c	707 MPa
Shear strength in 1-2 plane	S_{12}	125 MPa
Compression fracture toughness in transverse direction(1)	$\overline{G}_m^c$	2.25 kJ/m^2
Tensile strength in fiber direction	Y_t	594 MPa
Tensile fracture toughness in transverse direction(1)	$\overline{G}_m^t$	2,5 kJ/m^2
In-plane 1-2 shear intralaminar fracture toughness(1)	$\overline{G}_S$	2,5 kJ/m^2

(1) Taken from Donadon *et al*, 2008

The laminate thicknesses tested in this work were 2.1 mm (10 layers) and 4.2 mm (20 layers). The nominal thickness of each layer is 0.21 mm, with mechanical properties listed in Table 1. All plates had a quasi-isotropic lay-up sequence. The impact tests were performed in three different energy levels for each thickness. For the 2.1 mm thick laminate the chosen energy levels were 8, 16 and 28 Joules. For the 4.2 mm thick laminate the chosen impact energy levels were 12, 24 and 32 Joules. The laminate composite plate had the four edges clamped by means of the Boeing test window illustrated in Fig. 4.

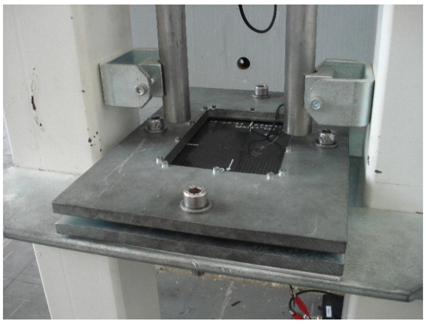


Figure 4. Coupon fixed within the Boeing test window

The drop test heights *H* for each impact test were set based on the chosen impact energy levels *E*, through the expression $H = E/mg$, where *m* is the mass of the impactor and g is the acceleration due to gravity. The values of the drop heights and the impactor masses used in the experiments are depicted in table 2.

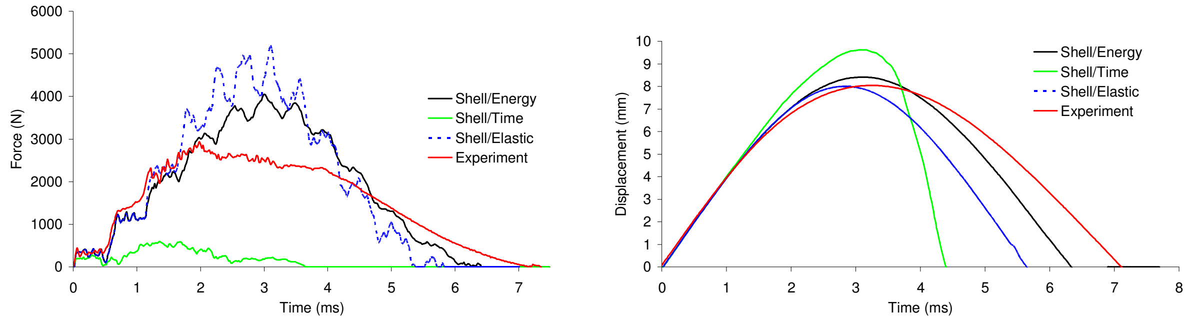
Table 2. Drop heights and the impactor mass

Laminate (number of plies)	**Height (m)**	**Impactor mass (kg)**
1 (10)	0.48	1.5314
1 (10)	1.00	1.5314
1 (10)	1.77	1.5314
2 (20)	0.81	1.5314
2 (20)	1.5	1.5314
2 (20)	2.05	1.5314

5. RESULTS

Simulations were carried out at three different impact energy levels to investigate the impact response of the composite laminates. In this paper only two cases are reported, namely impact tests at medium energy level (16 Joules for the 2.1 mm thick laminate and 24 Joules for the 4.2 mm thick laminate). In order to easily identify and separate the results a compact notation has been assigned for each case. The results obtained using the failure model based on energy are named as *Shell/Energy* and the results obtained using the failure model based on the time step degradation procedure are named as *Shell/Time.* By integrating the force time history, the impactor acceleration (A), velocity (V) and displacement (S) time histories were obtained.

Figure 5.a presents the force time history for the 2.1 mm thick laminate impacted at 16 Joules. The impact duration takes only 7.34 milliseconds and the peak load approximates a value of 2.88 kN. After 2.14 milliseconds the experimental force gradually decreases while the force predicted using the model *Shell/Energy* continues to raise. Consequently the energy based failure model was not capable of predicting the peak load very well. This may be due to the high values of the intralaminar fracture toughnesses used in the simulations, which were not measured for the material system studied in this work. However the model predicts relatively well the impact duration and the experimental deflection (Fig. 5.b). The specimens exhibited a visible damage area in both top and bottom faces, which clearly indicate the presence of matrix cracking and fiber failure due to the high bending stresses (Fig. 7.b). The predictions obtained using the *Shell/Energy* model indicates that matrix cracking and fiber failure occurs at 1.179 milliseconds and 2.92 milliseconds, respectively. The maximum deflection was accurately predicted by the energy based model (Fig. 5.b). Figure 6 presents the bending strains on the top and bottom faces of the plate. The *Shell/Energy* model predicts with relatively good accuracy the maximum bending strains compared to the experimental data. On the other hand, the *Shell/Time* model in general was not able to predict accurately the structural behaviour for this laminate.



(a) (b)

Figure 5. Force histories (a) and displacement vs. time at medium energy

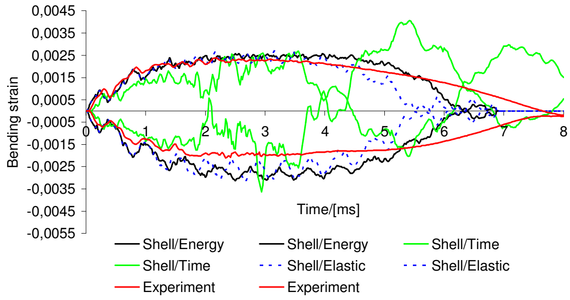


Figure 6. Bending strain at medium energy

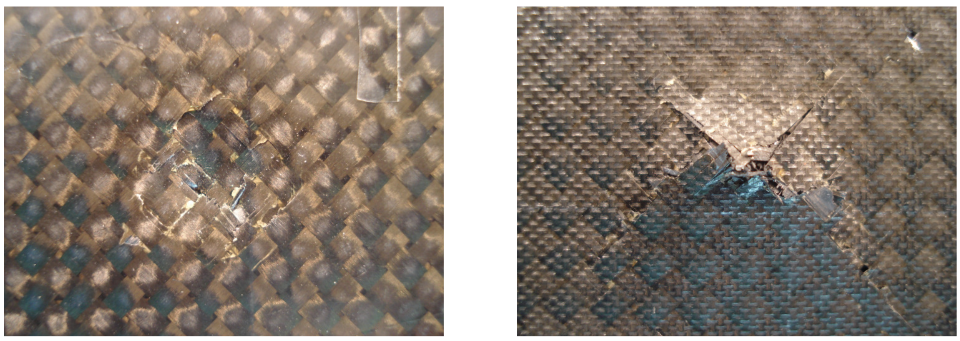


Figura 7. (a): Top face and (b): Bottom face of the impacted plate

For the 4.2 mm laminate, the force time history predicted using the energy based failure model correlates remarkably well with the experimental results, as shown in Fig. 8.a. The peak load was 6767.42 N and the impact duration for this case was 3.62 milliseconds. The *Shell/Energy* model also captures very well the impact duration. The average maximum experimental deflection was about 5.2 mm. However the bending strains were over predicted by the model, as shown in Fig. 9. Figure 10 clearly indicates the presence of matrix and fiber cracking at the bottom face of the laminate. The numerical results indicated tensile matrix failure at 0.58 milliseconds. Figures 8 and 9 illustrate that the predictions obtained using the failure model based on the time degradation procedure are very conservative. Thus, these results confirm that this failure model is not capable of predicting the impact response of the composite laminates studied in this work.

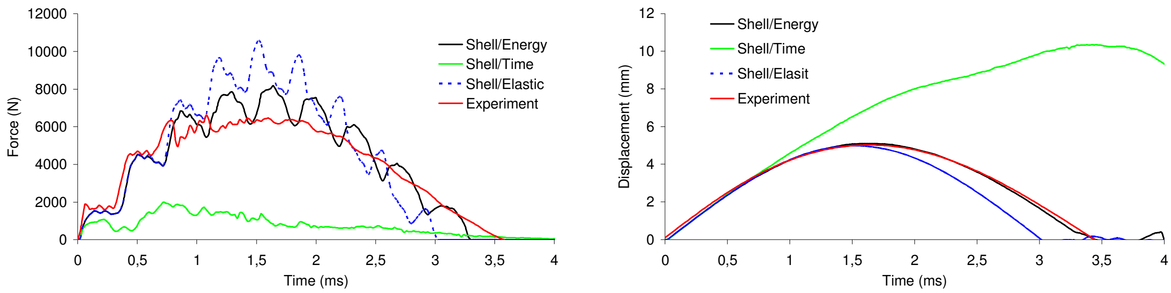


Figure 8. Force histories (a) and displacement vs. time at medium energy

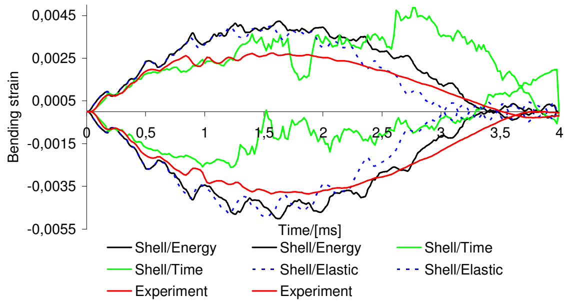
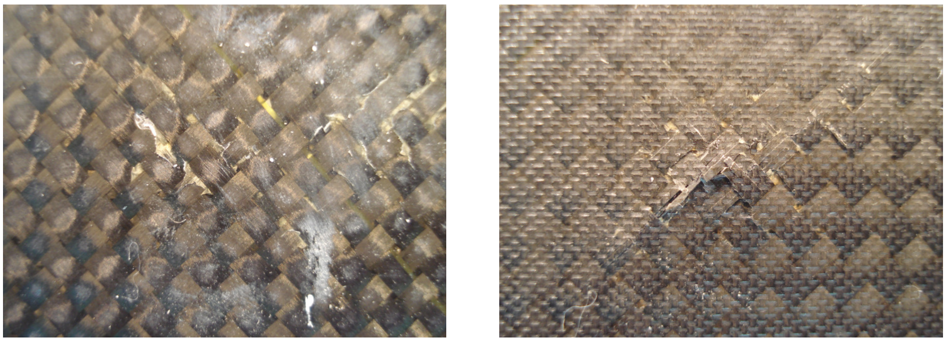


Figure 9. Bending strain at medium energy



(a) (b)

Figura 10. Front laminate face (a) and rear laminate face (b) after impact test at medium energy

6. CONCLUSIONS

An experimental and numerical study on the impact induced damage in composite laminates was presented in this work. The experimental tests were carried out at ITA using an in-house drop test tower. A series of coupons were used to investigate impact response of composite laminates. The capability of two different failure models was experimentally verified. The results indicated that the energy based failure model was capable of predicting damage initiation and damage growth with good accuracy. The accuracy of the model was validated by a direct comparison between numerical predictions and experimental results in terms of force, displacement and bending strain time histories. Nevertheless, a mismatch between experimental and numerical results was observed for some cases. This may be due to the high values used for the intralaminar fracture toughnesses associated with fiber and matrix failure, which were not measured for the material system studied in this work. Another reason would be the effects of delamination, which have not been included in the proposed failure model. The results obtained in this work also confirmed the poor performance of the failure models based on the time step degradation procedures.

7. ACKNOWLEDGEMENTS

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