LOW VELOCITY IMPACT AND COMPRESSION AFTER IMPACT SIMULATION OF THIN PLY LAMINATES

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Abstract
The ability to predict the damage resistance and the damage tolerance of a structure from potential impact events is of great importance in the aernautical industry. Virtual testing is a promising tool that could reduce the amount of tests. However, these analyses are computationally intensive and time consuming. Modelling thin ply laminates such as TeXtreme®, which is a fabric plain weave material, presents a modelling challenge due to their large number of plies. A procedure to simulate them efficiently within an explicit finite element analyses framework is described. Furthermore, important aspects on impact simulations such as the effect of the constitutive law and the number of interfaces for delaminations considered are studied. The tensile constitutive law mainly affects the interaction among damage mechanisms during the impact event, which are crucial for the compression after impact strength, while the compression constitutive law has smaller influence. For the studied case, the location and number of interfaces for delamination considered affect the compression after impact strength. However, there is a threshold in which the delamination does not change significantly and neither does it the compression after impact strength.

1. Introduction

Composite materials are used in the aeronautical industry. Impact events occur with some frequency on air-plane components. Therefore, the ability to predict the damage resistance as well as the damage tolerance of a structure from potential impact events is of great interest.

Impact damage models traditionally rely on either analytical models or empirical formulas. On the one hand, the complexity of the physical phenomena - geometric and material non-linearities, dynamic structural behaviour and loading, contact - limits the accuracy of analytical models. On the other hand, empirical formulas require extensive testing data which is time-consuming and costly. Virtual testing by means of non-linear Finite Element (FE) analyses is being used as a promising alternative that could reduce the actual amount of damage resistance and damage tolerance tests [1–3]. However, these analyses are computationally intensive and time consuming. It is of especial interest to reduce the computational

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effort while ensuring accuracy for design purposes. Besides this, thin ply laminates are increasingly used in the industry due to their well-known performance in laminated composite plates. Nevertheless, their large number of plies presents a modelling challenge.

The present work discusses modelling aspects that can improve the efficiency of the numerical models while keeping accuracy on the results. Furthermore, important aspects on low velocity impact (LVI) and compression after impact (CAI) simulations such as the effect of the constitutive law used and the number of interfaces for delaminations considered are discussed. On the one side, the constitutive law of the material is of paramount importance to accurately take into account the damage initiation and progression during a LVI event. On the other side, the number of delaminations is important to correctly account for the damage of the structure during an impact event [4]. Nevertheless, the number and location of delaminations might determine the critical load in damage tolerance analyses such as the CAI test. Both aspects are studied by means of a sensitivity analyses.

2. Experimental study and specimen configurations

The impact tests were performed using a CEAST Fractovis Plus instrumented drop-weight tower, with a 16 mm diameter and 5 Kg hemispherical impactor and an automatic anti-rebound impactor system. The rectangular specimens, which measures 150 by 100 mm, are placed over a flat support with a 125 mm by 75 mm rectangular cut-out. They are restrained during the impact by means of four rubber-tipped clamps, as suggested in ASTM D7136 standard test. Three different impact energy levels were tested: 20, 30 and 40 J with a minimum of 3 specimen samples per case. In the present work, it is only discussed the 30 J case.

According to the standard for CAI test (ASTM D7137), CAI tests were performed on a MTS Insight^{TM} Electromechanical tester with a 300 kN load cell. All the impacted specimens failed successfully under compression because they collapsed on the impacted zone.

The carbon fiber used in this study is Tenax® HTS45 with 12K filament yarn. The matrix is HexFlow® RTM 6 mono-component epoxy system, supplied by Hexcel®. The plies are presented as TeXtreme® plain weave with 20 mm wide yarn fabrics, manufactured by OXEON AB. The ply thickness considered is 0.08 mm (with 80 gsm areal weight).The fiber volume fraction is of 59 %. The method used to manufacture these thin plies is based on the spread-tow technology, at which conventional filament tows are thinned by increasing the tow width.

The selected stacking sequence is $[((45/-45)/(0/90))]_{14S}$, which is quasi-isotropic with conventional ply orientations. The orientation 0 is aligned with the major in-plane dimension (i.e. 150 mm). The nominal laminate thickness is of 4.48 mm which is a common value for drop-weight impact laboratory coupons. The laminates were manufactured by Aernnova - ESI using Resin Transfer Moulding (RTM) process.

The mechanical properties of TeXtreme® 80 gsm ply were tested at AMADE - University of Girona. Table 1 and 2 show the mechanical and fracture properties and oth the interface, respectively. The in-plane Young moduli is an average of the traction and compression moduli experimentally obtained.

3. Numerical modelling

The LVI as well as the CAI analyses were performed in Abaqus/Explicit. The CAI simulation was performed using the damage state at the end of the impact simulation as an initial condition.

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Table 1. Mechanical properties of TeXtreme® 80 gsm weave.

$E_1 = E_2$	E_3	G_{12}	$G_{13} = G_{23}$	ν_{12}	$\nu_{13} = \nu_{23}$
61400 MPa	8307 MPa	3782 MPa	3035 MPa	0.042	0.45

G_{IT}	G_{IC}	X_T	X_C	S_L
131 N/mm	77.5 N/mm	975.4 MPa	728 MPa	76.5 MPa

Table 2. Interface properties of TeXtreme® 80 gsm.

G_{Ic}	G_{IIc}	τ_{Ic}	τ_{IIc}	η
0.59 N/mm	1.0089 N/mm	55.47 MPa	72.54 MPa	3.1

Impact simulations are computationally intensive. Furthermore, many plies are used for TeXtreme® laminates. Therefore, the discretization of the model and the number of interfaces for delaminations should be suitably selected in order to achieve accurate results with reasonable CPU times.

It is proposed to use conventional shell elements which assume plane stress condition. This makes them less intensive computationally because their constitutive behaviour is simpler than 3-D solid elements.

Conventional shell elements with reduced integration were used in order to have the largest stable time increment ($\triangle t$) possible. Explicit dynamics procedure solves every problem as a wave propagation problem. To ensure a stable solution without oscillations the simulation time increment must be less than the stable time increment. The stable time increment is the minimum time that a dilatational wave takes to move across any element of the model.

The stable time increment of a continuum element can be estimated as:

$$\triangle t_{element} \leq L_e \sqrt{\frac{\rho}{E}} (\sqrt{1 + \zeta^2} - \zeta) \qquad (1)$$

where ρ is the material density, E the Young Moduli, ζ the fraction of critical damping and L_e is the shortest length of the element. In the case of 3-D elements such as continuum shell elements, the shortest length of the element might be the thickness. Conversely, the thickness of conventional shell elements does not penalize the simulation time, i.e. the stable time increment. Thus, very small thickness can be used without compromising the CPU time.

The sublaminate thickness is determined by the number and location of interfaces for delamination considered. One of the aims of this work is to study the effect of the considered number of interfaces for delaminations. The laminate has been divided by a different number of sublaminates equally spaced until reaching the actual amount of sublaminates, which is 56 plies. Table 3 summarizes the studied cases.

Table 3. Number of interfaces for delamination studied.

Number of sublaminates	Interfaces for delamination	Sublaminate thickness
2	1	2.24
4	3	1.12
8	7	0.64
14	13	0.32
28	27	0.16
56	55	0.08

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The intralaminar damage model employed as an Abaqus user subroutine for the simulations was proposed by Martín-Santos et al. [5] which uses simple loading functions. The failure criteria are maximum stress-based.

The model uses a bilinear cohesive law (see Fig. 1a) for each damage mechanim (M = 1, 2), which are the tensile and the compression mechanism in both principal directions of the material. The cohesive law is converted to an equivalent volumetric constitutive law (Fig. 1b) so as to be used in continuum elements. The constitutive behaviour for each damage mechanism (M) is defined by the elastic moduli (E_M), the fracture toughness (G_M), the strength (X_M), the factor which determines the pull-out stress (f_{X_M}) and the characteristic finite element length (l^*).

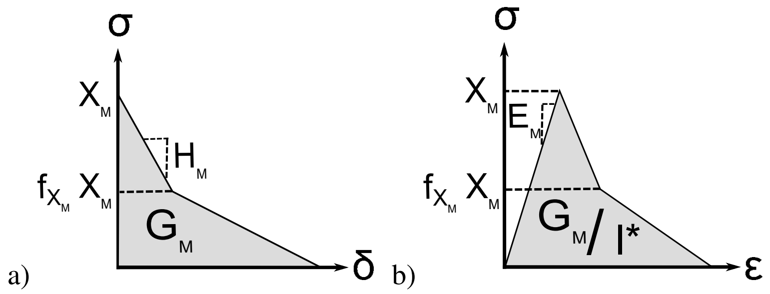

Figure 1. a) Cohesive bilinear law (stress-opening) and its b) volumetric equivalent constitutive law (stress-strain).

The constitutive law shape of the studied material is not known. Therefore, a sensitivity analysis was done to study its effect on the LVI and CAI results. Fig. 2 shows the four investigated constitutive laws; two for traction and two for compression damage mechanisms. The only change is the shape, which is controlled by the parameters H_M and f_{XM}, the material properties are from Table 1.

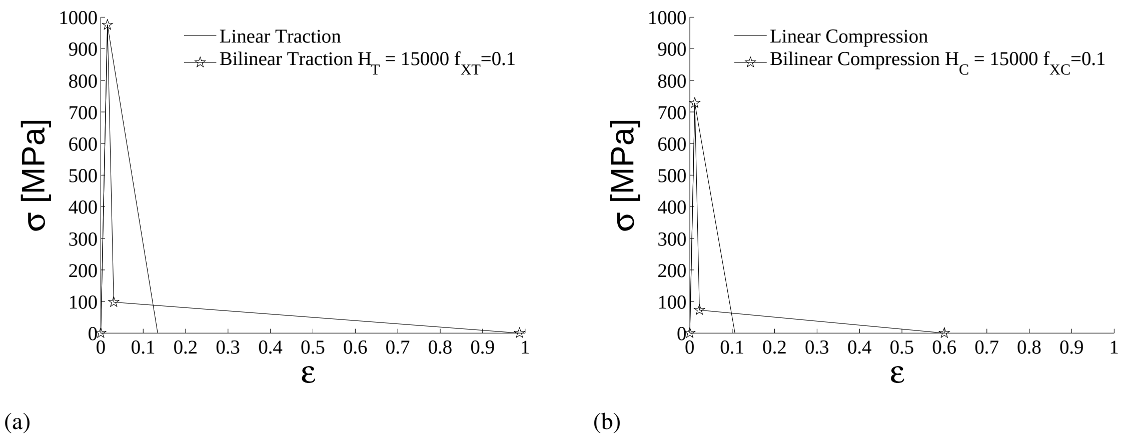

Figure 2. (a) Traction and (b) compression constitutive law shapes considered for the sensitivity analyses.

The employed intralaminar damage model is meant for fabric plies assuming plane stress conditions. TeXtreme® material is a fabric ply with wide yarns which makes it quite similar to an UD tape. However, it is modelled using the fabric constitutive model from Martín-Santos et al. [5] since the material properties were obtained for homogenised plies (see Table 1 and 2). The model considers isotropic hardening to account for the in-plane shear plastic behaviour. Nevertheless, the model does not consider any damage under shear loading.

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The Crack Band Model algorithm [6] is implemented in the constitutive model to reduce the influence of mesh refinement on the numerical prediction during damage growth. The selected mesh size was 2 mm which guarantees no snap-back for the constitutive laws considered (see Fig. 2) and a reasonable computational time. The mesh size was kept to 2 mm for all the simulations in order to avoid changes in the constitutive law, which depends on the characteristic element length (l^*).

To avoid problems related to excessive distortion, which often stops explicit analysis, a maximum value of the damage variable is defined for element deletion. However, it is worth noting that this definition can have an effect on the fracture toughness property and as a consequence on the structure dissipated energy. Depending on the constitutive model used, the damage variable can evolve at high values at relatively small dissipated energies. In the present simulations a value of 0.9999 was used which ensures to dissipate the 99.9 % of the fracture toughness.

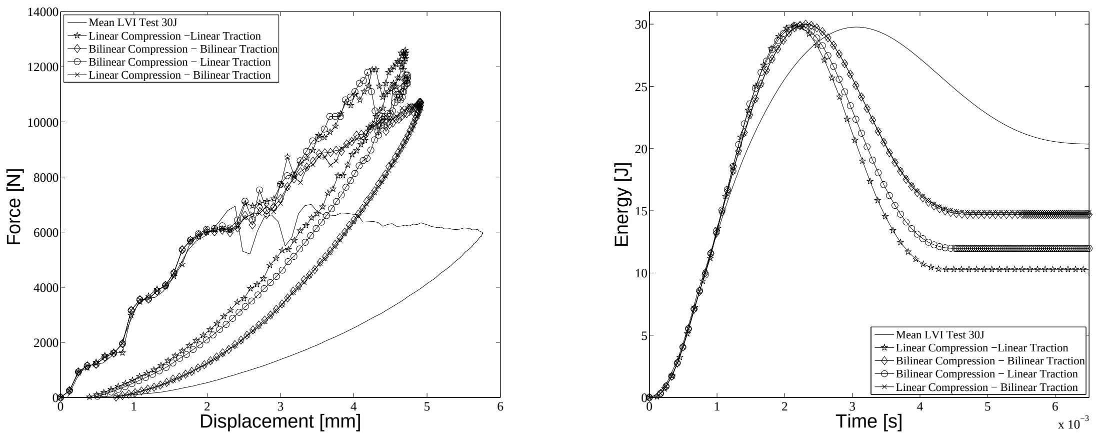
To model delamination cohesive elements were used. The interlaminar damage model used as an user subroutine is the proposed by González et al. [7]. A linear cohesive law is assumed which offers the best compromise between computational cost and accuracy, as Alfano studied [8]. The penalty stiffness value adopted for all the simulations was $k = 5\ 10^5$ N/mm^3. To avoid affecting the stable time increment due to the element thickness, zero-thickness cohesive elements were used.

4. Results

In order to perform a manageable comparison of the LVI and CAI test, the mean values of the experimental tests are used.

4.1. Low velocity impact

The results from the sensitivity analyses on the effect of the constitutive law are shown in Fig. 3. It is for the case in which all the interfaces for delamination are considered. The constitutive law for damage compression do not affect the LVI results. However, the results become fairly sensitive to the traction constitutive law.



(a) (b)

Figure 3. LVI test 30J. Experimental and numerical force-displacement response (a) and energy absorption evolution (b) for different constitutive laws. The numerical results are for the 56 sublaminates case.

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The modelling strategy is able to correctly catch the elastic range (see Fig 3. However, the damage mechanisms are not correctly reproduced. The energy is not sufficiently dissipated through damage mechanisms. The causes could stem in some simplifications of the constitutive model and some uncertainties on the data reduction of experiment test results such as the fibre fracture toughness.

4.2. Compression after impact

The CAI results show that the compression constitutive law has an influence in the way it fails the specimen and the CAI strength (see Fig. 4). Nevertheless, the CAI strength is more controlled by the damage developed during the LVI.

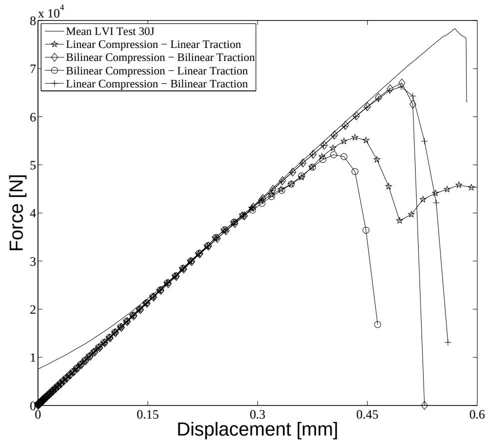
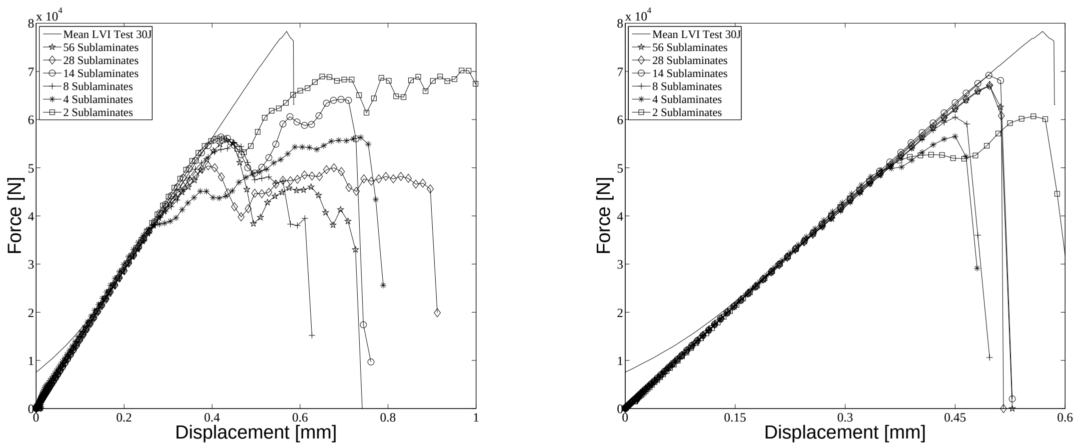


Figure 4. CAI test. Experimental and numerical force-displacement response for different constitutive laws. The numerical results are for the 56 sublaminates case.

In the simulations performed there was more interlaminar damage (i.e. delamination) when a linear traction constitutive law was used than for the cases with a bilinear one. For this reason, the CAI strength are lower for the cases with linear traction constitutive law independently of the compression constitutive law employed (see Fig. 4).



(a) (b)

Figure 5. CAI test. Experimental and numerical force-displacement response for different number of interfaces. The numerical results are for the (a) Linear-Linear and (b) Bilinear-Bilinear constitutive laws.

On the other hand, the effect of the number of interfaces for delamination considered in the model is shown in Fig. 5. The delamination area does not change as long as there are sufficient interfaces for delamination during the LVI. For the studied case, it occurs when more than seven interfaces were considered. Thus, the CAI strength does not significantly change.

5. Conclusions

A modelling procedure to simulate damage resistance and damage tolerance on thin ply weaves laminates has been proposed. The procedure is based on the use of shell elements and a simplified constitutive behaviour. The modelling procedure has allowed to perform simulations of TeXtreme® 80 gsm in a reasonable computational time. The simulation time of the LVI plus CAI ranged from 0.5 hours (2 sublaminates) to 18 hours (56 sublaminates) with 10 CPU's in a Intel Xeon 3.10 GhZ processor. This made possible to perform a sensitivity analyses on the effect of the constitutive law shape and the role of the number of interfaces for delamination considered in the model.

The results obtained showed very good agreement at the elastic range, which validates the selected modelling approach. However, the damage mechanisms were not well predicted for the considered constitutive law shapes. Further investigations will be devoted to find the causes, which could stem in the simplifications of the constitutive model and the considered constitutive law shapes.

The sensitivity analyses showed the importance of the traction constitutive law for LVI and CAI simulations. It affects the interaction damage mechanisms during a LVI event. This has consequences in the CAI test. On the other hand, the compression constitutive law seems to be less crucial for the studied material.

The number of interfaces for delamination considered did not have a significant influence on the LVI results. However, the lower the number of interfaces the larger the projected delamination area. This occurs until a minimum number of interfaces for delamination in which it does not change any more. Consequently, it neither changes the CAI strength significantly.

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