Composite Structures 203 (2018) 172–181

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Numerical study of composite fragment impacts onto rigid target

J. López-Puente[a],*, A. Mata-Díaz[b], J. Pernas-Sánchez[a], J.A. Artero-Guerrero[a], D. Varas[a]

[a] Department of Continuum Mechanics and Structural Analysis, Universidad Carlos III de Madrid, Avda. de la Universidad, 30, 28911 Leganés, Madrid, Spain
[b] Gestamp Servicios SA, Calle Alfonso XII 16, 28014 Madrid, Spain

ARTICLE INFO

Keywords:
Composite
Fragment
High-velocity impact
Numerical
Progressive damage analysis
Hashin model

ABSTRACT

In this work, it is proposed a numerical methodology to model the behaviour of composite laminates when they act as impactors at high velocity. The numerical model uses an intralaminar criterion based in the Hashin model and a Progressive Damage model to describe the ply behaviour, whereas the interlaminar failure is taken into account by means of cohesive interactions. The validation of the model is performed attending the kinematics and erosion of the laminate during the impact process onto a rigid target as well as the force and impulse generated. Once validated, the model is used to analyse the influence of the fragment miss-alignment in the impact process.

1. Introduction

The reduction in fuel consumption of the commercial aircraft is achieved, mainly, because of the structure lightening and the improvement of the engines. In both cases composite laminates play a very important role, since they exhibit outstanding specific mechanical properties. The main drawback of CFRPs (from the structural point of view) is the poor performance against impact when it occurs perpendicularly to the laminate plane. Understanding the behaviour of laminates subjected to that kind of impacts is of great importance since the use of those materials (in particular carbon/epoxy, CFRP) in aircraft structures has reached approximately 50% (in terms of weight).

Composite laminates are increasingly used in aircraft engines, both in the fan blades and in the engine case, which in case of an uncontained failure, could impact the CFRP fuselage. In addition the new open-rotor engines, which probably will propel future aircrafts, use counter rotating blades, without fan case protection, manufactured using composite laminates that also could impact the fuselage in case of failure. In the framework of the CleanSky 2 program (which belongs to the Horizon 2020 program of the European Commission) there is an activity with the objective of demonstrate the performance of this new engine. One of the main challenges is the need of protection of the aircraft fuselage against the possible impact of one of those blades. Those examples show the importance of studying the behaviour of carbon/epoxy laminates acting as impactors at high velocity.

The behaviour of composite laminates under dynamic loading conditions (as a structural component) has received relevant attention from many authors. The failure mechanisms and the influence on the CFRP response of different variables such as impact velocity [1], projectile geometry, projectile obliquity or temperature have been widely analysed experimentally [1–3]. In addition, researchers have made a great effort on developing numerical models to reproduce the different damage mechanisms that appear in laminates under impact conditions studying the influence of different projectile shapes, obliquity or materials using different approaches [4–15].

The analysis of how a composite fragment behaves as an impactor at high velocity has received almost no attention from other researchers. The most similar works are those which studied the crushing of composite tubes. In this field it is possible to find some static analysis and also studies of tubes reinforced with foams or even aluminium. Mamalis et al. [16,17] analysed the dynamic compression of pure CFRP tubes from a numerical and experimental point of view. The main objective of those works was related to the study of the energy absorbed during the crushing process. Recently H.A.Israr et al. [18,19] published interesting studies, both experimental and numerical, regarding the laminates crushing. They show the failure process of the laminate during the impact, being able to identify the different failure modes involved in the process. It is worth to say that the last mentioned works study quasi-static cases and low velocity impacts as well as that the specimens were cut to form a chamfering-type trigger mechanisms. The failure mechanisms and the impact process of a laminate without chamfer impacting at high velocity could be different.

The authors of the current work have studied this type of impact, from the experimental point of view [20], launching composite fragments by means of a pneumatic launcher in a range of impact velocities between 70 to 180 m/s. Prior to perform an impact of a composite

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* Corresponding author.
E-mail address: jlpuente@ing.uc3m.es (J. López-Puente).

https://doi.org/10.1016/j.compstruct.2018.07.002
Received 22 March 2018; Received in revised form 28 June 2018; Accepted 2 July 2018

fragment against a composite panel, it was considered more interesting to carry out a simpler test in order to study the failure mechanisms that appear in the CFRP fragment during the impact. The impact force that a composite fragment at high velocity induces is of great interest for the aircraft industry in order to design structures that could withstand such kind of loads. The force induced by the impact of a composite fragment will depend on the flexibility of the structure where impacts; as the flexibility increases, the force diminishes. When the fragment impacts a rigid plate, the force induced will be the highest possible, and hence it could be considered the worst-case scenario.

The objective of this work is to develop a numerical methodology to predict the behaviour of carbon/epoxy unidirectional fragments when impacting a rigid plate in a range of velocities between 70 to 180 m/s. The numerical model uses an intralaminar criterion based in the Hashin model and a Progressive Damage model to describe the ply behaviour, whereas the interlaminar failure is taken into account by means of cohesive interactions. The validation of the model is performed attending the kinematics and erosion of the laminate during the impact process onto a rigid target, as well as the force and impulse generated. The experimental results are obtained from a previous work of the current authors [20]. Once validated, the model is used to analyse the influence of the fragment miss-alignment in the impact process.

Although there are numerous numerical works dealing with the modelling of laminates, it was not possible to find any numerical work regarding the analysis of a composite laminate impacting at high velocity against other surface. Therefore developing a numerical methodology capable of reproduce this kind of impacts or even reaching some conclusion about which kind of failures should be taken into account in the model, could be of great interest.

2. Material modelling

In order to predict the behaviour of unidirectional composite fragments impacting at high velocity, a numerical methodology has been developed using the commercial explicit finite element code Abaqus/Explicit v6.12. This software has been specifically designed to simulate dynamic events with important non-linearities (material and geometrical), which both appear in the problem studied in the current work.

In order to model the behaviour of a unidirectional composite laminate is necessary to use a intra-laminar failure criteria to describe the failure inside the plies, and a inter-laminar model to define the behaviour between the plies. To obtain precise results, the model should consider all the laminate plies and every inter-ply. In the following sections, the material modelling is described.

2.1. Intra-laminar failure and damage evolution

The composite laminate behaves as an orthotropic elastic material until damage starts. The Hashin and Rotem model [21] has been used to model the intra-laminar failure; this material is already implemented in the software material library, to be used with shell (or continuum shell) elements. The aforementioned model is implemented in the code using a progressive damage analysis that is a generalization of the approach proposed by Camanho and Davila [22]. In this section a brief description of the model is performed; further details could be found in the software documentation [23]. In this model, the onset of damage is defined by the Hashin and Rotem damage initiation criteria [24], which adequately predicts the different intra-laminar failure mechanisms. Once it occurs, the damage will evolve degrading the material stiffness coefficients until the energy dissipated is equal to the fracture toughness (divided by the element characteristic length), when the material is fully damaged. Four different uncoupled damage initiation criteria are defined as follows:

- Fibre failure under tension ($\hat{\sigma}_{11} \geqslant 0$)

$$F_t^f = \left(\frac{\hat{\sigma}_{11}}{X_T}\right)^2 + \alpha\left(\frac{\hat{\sigma}_{12}}{S_L}\right)^2 \qquad (1)$$

where $\hat{\sigma}_{ij}$ are the components of the effective stress tensor (with no damage) proposed by Matzenmiller et al. [25], X_T and S_L are the tensile (in the fibre direction) and in-plane shear strengths of the laminate, and α is a parameter that allows to calibrate the contribution of the in-plane shear stress in the failure criterion. In order to not overestimate the contribution of the in-plane stress, the parameter α must be less or equal than 1, and positive. In this case its value is $\alpha = 1$.

- Fibre failure under compression ($\hat{\sigma}_{11} < 0$)

$$F_c^f = \left(\frac{\hat{\sigma}_{11}}{X_C}\right)^2 \qquad (2)$$

where X_C is the compressive strength of the laminate in the fibre direction.

- Matrix failure under tension ($\hat{\sigma}_{22} \geqslant 0$)

$$F_t^m = \left(\frac{\hat{\sigma}_{22}}{Y_T}\right)^2 + \alpha\left(\frac{\hat{\sigma}_{12}}{S_L}\right)^2 \qquad (3)$$

where Y_T is the tensile strength of the laminate in the matrix direction.

- Matrix failure under compression ($\hat{\sigma}_{22} < 0$)

$$F_c^f = \left(\frac{\hat{\sigma}_{22}}{2S_T}\right)^2 + \left[\left(\frac{Y_C}{2S_T}\right)^2 - 1\right]\frac{\hat{\sigma}_{22}}{Y_C} + \left(\frac{\hat{\sigma}_{12}}{S_L}\right)^2 \qquad (4)$$

where Y_C and S_T are the compressive (in the matrix direction) and out-of-plane shear strengths of the laminate.

All the material properties, shown in Table 1, are obtained from the literature and the manufacturer data-sheet.

Once any of the failure initiation criteria reaches the value of one, any additional strain increment will reduce the values of stiffness of the element in the corresponding direction following a linear evolution law (Fig. 1). This decrease depends on the energy dissipated during the process (see work of Turon et al. [28]), since the area under the triangle should be equal to the material fracture toughness divided by the element characteristic length.

Each damage initiation mechanism has its own damage variable that controls the stiffness degradation, and its value goes from zero (undamaged) to one (fully damaged). The stiffness tensor C_d, that relates the stress and the strain (written in vectorial form) is:

Table 1
Carbon epoxy AS4/8552 properties from the manufacturer Hexcel and literature [26,27].

Property	Symbol	Magnitude	Units
Density	ρ	1580	kg/m^3
Young modulus 0°	E_1	135	GPa
Young modulus 90°	E_2	9.6	GPa
In-plane shear modulus	G_{12}	4.5	GPa
Out-plane shear modulus	$G_{13} = G_{23}$	5.3	GPa
Poisson coefficient 12	ν_{12}	0.32	–
Compressive strength 0°	X_C	1531	MPa
Tensile strength 0°	X_T	2207	MPa
Compressive strength 90°	Y_C	158	MPa
Tensile strength 90°	Y_T	73	MPa
In-plane Shear strength	S_L	114.5	MPa
Out-of-plane Shear strength	S_T	102.3	MPa
Ply tensile fracture energy 0°	G_{1+}	81.5	kJ/m^2
Ply compression fracture energy 0°	G_{1-}	106.3	kJ/m^2
Ply tensile fracture energy 90°	G_{2+}	0.28	kJ/m^2
Ply compression fracture energy 90°	G_{2-}	1.313	kJ/m^2