Composites Part B 107 (2016) 9–21

Contents lists available at ScienceDirect

Composites Part B

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

Low-velocity impact tests on carbon/epoxy composite laminates: A benchmark study

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ARTICLE INFO

Article history:
Received 2 August 2016
Received in revised form
13 September 2016
Accepted 20 September 2016
Available online 22 September 2016

Keywords:
PMCs
Impact behavior
Delamination
Ultrasonics
Post-impact indentation depth

ABSTRACT

Low-velocity impacts (LVI) on composite laminates pose significant safety issues since they are able to generate extended damage within the structure, mostly delaminations and matrix cracking, while being hardly detectable in visual inspections. The role of LVI tests at the coupon level is to evaluate quantities that can be useful both in the design process, such as the delamination threshold load, and in dealing with safety issues, that is correlating the internal damage with the indentation depth.

This paper aims at providing a benchmark of LVIs on quasi-isotropic carbon/epoxy laminates; 2 laminates are tested, 16 and 24 plies and a total of 8 impact energies have been selected ranging from very low energy impacts up to around 30 J. Delamination threshold loads, shape and extension of delaminations as well as post-impact 3D measurements of the impacted surface have been carried out in order to characterize the behavior of the considered material system in LVIs.

The analysis of test results relevant to the lowest energies pointed out that large contact force fluctuations, typically associated to delamination onset, occurred but ultrasonic scans did not reveal any significant internal damage. Due to these unexpected results, such tests were further investigated through a detailed FE model. The results of this investigation highlights the detrimental effects of the dissipative mechanisms of the impactor. A combined numerical–experimental approach is thus proposed to evaluate the effective impact energies.

1. Introduction

The design and the certification of aerospace composite structures deal with contrasting, yet mutually interactive, aspects of composites in the sense that if the design, on the one hand, can benefit from the excellent material properties leading to lightweight and efficient structures, the certification, on the other hand, must consider the most detrimental scenarios that can be encountered by the structure. Fatigue, environmental conditions and, in particular, manufacturing and low-velocity impact damage are responsible of the rather low allowables (compared to the pristine material potential) that are usually adopted in the design process.

Low-velocity impacts represent a serious safety concern since extended damage could be present in the composite structure although scarcely detectable by visual inspections. In this context, the threshold of reliable detection is named Barely Visible Impact Damage (BVID). Damage lower than the BVID threshold must not reduce the strength of the structure below its ultimate load capability [1].

In the aerospace industry, the characterization process of a particular material system usually makes use of a pyramidal approach, known as the Building Block Approach (BBA). The idea is to perform the material characterization at increasing levels of complexity taking into account, for example, the effects of geometry, loads and environment. In particular, the airworthiness authorities require experimental evidence of the capability of a composite structure to withstand prescribed loads in the presence of damage. Starting from simple geometries, it is thus fundamental to evaluate both the damage scenarios and, successively, the residual strength, particularly in compression, of composite structures.

Clearly, the resulting damage scenarios and consequently the strength of the damaged structure can depend on many testing

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http://dx.doi.org/10.1016/j.compositesb.2016.09.057

parameters such as the clamping conditions, the dimensions of the impactor tip and the impactor mass [2,3]. As an example [4], presents the results of an investigation on the mechanical response and on the delamination extension on quasi-isotropic thick composite plates subjected to uniaxial tension preload.

An interesting property that can be extracted from the mechanical response of low-velocity impact tests and that can be used in the design process, is the Delamination Threshold Load (DTL). The use of the impact energy as a design parameter to take into account impact damage would prove wrong. In fact, the impact energy threshold related to damage initiation is strongly dependent on impact location, component dimensions and boundary conditions. Yet, many studies [5–8] have pointed out that damage onset occurs when the impact force reaches a critical value, that is the DTL. This value, for composite laminates, depends only on the mechanical properties of the material system and on the laminate thickness. In Ref. [6] a vast LVI experimental database (containing approximately 500 test records) is analyzed to provide strong evidences for the existence of the Delamination Threshold Load (DTL). The results showed that the DTL was clearly identifiable for all the force–time histories that reached values higher than the DTL.

The force–time histories obtained in LVIs represent global information from which the shape and the extensions of the damage induced in the structure cannot be known. LVIs causes extensive delaminations and matrix cracking [9], in particular delaminations can detrimentally affect the structure stiffness and can significantly lower the residual strength of the structure in compression [10–12].

Through ultrasonic inspections one can correlate the severity of the damage (extension of damage) and the nominal impact energy [13]. These data are particularly useful if they are also correlated with the measurements of the depth of the indentation left by the impact event. In fact, if, on the one hand, the damage extension influences the compressive residual strength, the indentation depth is related to safety issues through the capability of identifying damaged structures in visual inspections.

The present work aims to build up a comprehensive dataset of low-velocity impact tests on quasi-isotropic carbon/epoxy laminates to serve as a reference for tuning and validation of numerical analyses employing advanced damage models.

The experimental campaign consists in impacts on 24 specimens with quasi-isotropic lamination of 2 different thicknesses, 16 and 24 plies. In addition to the typical contact force–time histories, usually measured in impact tests, ultrasonic inspections, from which the shape and the extension of damage are captured, are carried out and the impacted surfaces are 3D scanned to measure the indentation depths. Moreover, the experimental database is complemented with the results of an *ad hoc* experimental characterization of the composite material system used for the LVI tests [14].

For each laminate, 4 increasing values of nominal impact energy have been selected in order to obtain different damage scenarios. To limit the impact velocity at the highest energies, 2 different impactor masses have been used.

For the impact tests performed with the smaller mass, unexpected results have been obtained. Such tests have been further investigated by means of a detailed FE element model which helped to highlight the presence of dissipative mechanisms within the impactor. Then, through a combined numerical-experimental approach the effective impact energy, that is the one actually transferred to the specimen, is evaluated.

2. Overview of the LVI campaign

An experimental campaign of low-velocity impacts has been performed on quasi-isotropic carbon/epoxy laminates. The tests have been carried out at the I2M laboratory of the Institut de Mécanique et dflIngénierie (Bordeaux, France). A total of 24 impacts have been performed on two batches (12 specimens each) of 8150 × 100 mm laminates manufactured by stacking 16 and 24 unidirectional plies of Tenax J HTA 5231 6K/Cycom 985 prepreg. The specimens have been manufactured according to material and process specifications compliant to aerospace industrial production standards.

The elastic lamina properties, shown in Table 1, have been evaluated in an experimental campaign aimed at characterizing the used material system and carried out in the structural laboratory of the Department of Civil and Industrial Engineering at the University of Pisa [14].

For the sake of simplicity, specimens belonging to each batch are identified, throughout this paper, with the “LAM16” label for the 16-ply specimens and with the “LAM24” label for the 24-ply specimens. The manufactured stacking sequences are $[0/+45/-45/90/]_{S2}$ and $[0/+45/-45/90/]_{S3}$ with measured average thicknesses of 2.32 mm for the 16-ply batch and 3.82 mm for the 24-ply batch.

Table 2 shows the specifications of the performed impact tests on the LAM16 and LAM24 batches. The impact energies have been selected by establishing 4 values ranging from a low energy up to a maximum one computed assuming, approximately, a ratio of impact energy to specimen thickness equal to 6.7 J/mm, as specified by ASTM D7136 [16]. Two impactor masses (2.5 kg and 4.6 kg) are used in order to avoid having excessive impact velocities at the higher impact energies.

From an operative point of view, each nominal impact energy, E_{Impact}, is obtained by setting the distance, h, between the surface of the specimen and the impactor tip computed through the energetic balance $Mgh = E_{Impact} = ½MV^2$ where M is the impactor mass, g is the gravitational acceleration and V is the velocity of the impactor just before the impact takes place.

The tests have been conducted with a drop weight tower consisting of two rigid steel columns firmly connected to a metallic gantry. The falling impactor is linked to an electromagnet used to vertically move the impactor up to the desired height. A 16-mm-diameter steel impactor cap, connected to a piezoelectric sensor, is used to carry out the impacts and to measure the impact force. The impact velocity is measured through a laser sensor while an anti-rebounce system is used to avoid producing multiple impact damage on the same specimen.

A rigid fixture, compliant to the requirements reported in Ref. [16], has been used to hold the specimens. The fixture is mounted by means of 4 rigid columns onto a rigid steel base fixed to the ground. Three lateral guiding pins are assembled on the fixture to correctly position each specimen while four clamps hold the specimen during the impact. Fig. 1 shows details of both the impactor and the fixture used in the tests. To perform the impact tests with the 4.6 kg impactor, additional weights have been added to the impactor. The additional masses are fixed to the lower forks and held still through long screws connecting the two forks (see Fig. 1 (a)).

3. Force–time histories of the LVI tests

The force–time histories obtained in the impacts on the LAM16 and LAM24 specimens, sampled at 30 kHz, are shown in Figs. 2 and 3, respectively.

Table 1
Elastic properties of the carbon/epoxy material system.

E_{11}	112.7	$[GPa]$	G_{23}	3.64	$[GPa]$
$E_{22} = E_{33}$	10.35	$[GPa]$	$\nu_{12} = \nu_{13}$	0.32	[–]
$G_{12} = G_{13}$	3.50	$[GPa]$	ν_{23}	0.42	[–]