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Compressive residual strength at low temperatures of composite laminates subjected to low-velocity impacts

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Abstract

Compression after impact behaviour of different carbon fibre reinforced composite laminates (tape and woven) was studied at low temperatures. Low-velocity impact tests on thin plates at room temperature were made, followed by compression after impact tests at −60 °C and −150 °C. The results of these tests were compared with those of non-impacted specimens to study the variation of the residual strength at different impact energies. In tape laminates, the lower temperature decreased compression after impact strength, although no influence was detected regarding temperature in the variation of the compressive-strength-retention factor. However, at low temperatures, the woven laminate showed greater strength and a less loss of the retention factor than at room temperature.

Keywords: Compression after impact; Thin laminates; Low temperature; Residual strength; Carbon fibre laminates

1. Introduction

Composite materials, mainly carbon fibre/epoxy laminates, are being widely used to manufacture structural components that are exposed to low temperature environments in aeronautical and aerospace applications [1]. Competition between aeronautical constructors has stimulated the use of composites in primary structures (wings or fuselages), as in the future Airbus 350 or Boeing 787. In addition, the use of composites in the manufacture of cryogenic fuel tanks is one of the most promising technologies to decrease the weight of the future reusable launch space vehicles [2–5].

In these structural components, unidirectional laminates are not normally used because of the high anisotropy of their mechanical properties; multidirectional laminates, basically quasi-isotropic and woven, are optimal for different load conditions [6]. Although the use of cross-ply laminates in industrial applications is less usual, it would be helpful to know the behaviour of the components manufactured from these laminates, since these multidirectional ones are the easiest to make and direct comparisons could be established with the plain-woven laminates [7].

Unfortunately, composite laminates have low resistance under dynamic loading, particularly impact loading, which can significantly reduce their mechanical properties [8]. Structural components may undergo low- and high-velocity impact loading during their manufacture, assembly, maintenance or service life (runaway debris, bird strikes, dropped wrench, etc.), low-velocity impacts being considered more dangerous. Low-velocity impact damage occurs mainly in the form of delamination, which may involve single or multiple internal cracks parallel to the surface of the structure or component. Under compressive loading, this local delamination may grow and lead to global failure of the structure at a load well below that of the design level [9]. Several researchers [10–13] have shown that the compressive-strength in a damaged component may have only 40% of that of an undamaged structural element.

Therefore, for an appropriate design, it is important to ensure that the residual strength of a damaged structure

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is sufficient either for service until the damage is detected or for the rest of the service life of that structure. For this reason, numerous studies have examined the behaviour of composite laminates subjected to low-velocity impacts and compression after impact, mainly at room temperature [11–18].

Most low-velocity impacts occur during maintenance or assembly operations, and thus at ambient temperature, but the damaged components may work under low temperatures during their service life, exposed to air at −60 °C or in space at −150 °C [8,19]. Great changes in the structure, properties and failure mechanisms of composite materials can occur when they are exposed to low temperatures [20–22]. Some authors have pointed out that in carbon fibre composites the reduction of temperature may increase the compressive and tensile strength in the fibre direction [23], whereas others report reductions in compressive [24] or tensile strength [2]. Consequently, it is necessary to determine the mechanical behaviour of these components damaged at ambient temperature when the temperature in service is very low. Bibliographical references have not been found about this matter.

In this paper, a study is made of the compressive residual strength at low temperatures of carbon/epoxy laminates of different configurations: cross-ply $[0/90]_{3S}$, quasi-isotropic $[\pm 45/0/90]_S$ and woven (10 plies). First, low-velocity impact tests were made at ambient temperature, damaging the specimens and afterwards the effects of that damage on the compressive strength of the laminates exposed at low temperatures were analysed.

2. Experimental tests

2.1. Materials

Three different carbon/epoxy laminate lay-ups were tested: a cross-ply $[0/90]_{3S}$ and a quasi-isotropic laminate $[\pm 45/0/90]_S$, both manufactured from unidirectional pre-impregnated sheets of AS4/3501-6, and a laminate of ten plain-woven plies, AGP-193-PW/8552.

All the laminates were manufactured by SACESA (Spain) using prepegs of Hexcel Composite Materials with a volumetric fibre content of 60%, following all the requirements of the aeronautic industry.

2.2. Low-velocity impact tests

Low-velocity impact tests were performed at room temperature using a drop-weight tower, CEAST Fractovis 6785. Square specimens of 78 mm × 78 mm were tested. The impactor had a semi-spherical tip of 20 mm of diameter and a total mass of 3.62 kg.

Four different impact energies were exerted on each laminate (Table 1). All energies were below the one that produces the perforation of the laminate. As the laminates were of different thicknesses, and thus the energy to perforate also differed in each laminate, different impact energies were used. Six specimens per laminate and impact energy were tested. All these tests were carried out at room temperature (20 °C).

Table 1
Impact energies used in the tests of the different laminates

Laminate	Impact energy (J)			
Cross-ply $[0/90]_{3S}$	1	3	4	6
Quasi-isotropic $[\pm 45/0/90]_S$	2	3	4	5
Woven (10 plies)	4	7	10	13

Each test provided a record of the force applied by the impactor on the specimen and the initial velocity at the moment of impact. From this signal, and under the hypothesis of permanent contact between specimen and impactor, the displacement of the contact point (Eq. (1)) and the absorbed energy up to failure (Eq. (2)) were determined by successive integrations.

$$x(t) = x_0 + \int_0^t \left[v_0 - \int_0^t \frac{F(t) - P}{m} \mathrm{d}t \right] \mathrm{d}t \qquad (1)$$

$$E(t) = \int_0^t F(t) \left[v_0 - \int_0^t \frac{F(t) - P}{m} \mathrm{d}t \right] \mathrm{d}t \qquad (2)$$

2.3. Compression after impact tests

A compression test of the impacted specimens was conducted to analyse how its strength was reduced by the impact damage. The compression tests were carried out at low temperatures (−60 °C and −150 °C), to reproduce the conditions to which the aeronautical and aerospace structures could be subjected during their service life. The results were compared with CAI tests carried out by the same research team at room temperature (20 °C) [13].

It was not possible to follow the recommendations of ASTM D 7137/D7137M-05 standard [25] since it refers only to the test of laminates thicker than 4 mm, and the thickness of the specimens used in this study was 1.6 mm in the quasi-isotropic laminate and 2.2 mm in the cross-ply and the woven laminate.

For the compression after impact tests, a new device developed by the same research team [13] was used. It allows thin laminates to be tested without altering their geometry in the cutting to make them more slender and thus the damage caused by impact; and the use of tabs is not necessary to perform the compression test, as other authors do [12,14,15,17]. This device can be adapted to different specimen thicknesses. It was made of stainless steel for tests at low temperatures.

The device (Fig. 1) was placed in an Instron climatic chamber connected to a universal Instron testing machine of 100 kN. The low temperatures were reached using liquid nitrogen. As a means of avoiding erroneous signals due to the cooling of the load cell, it was isolated by a cylindrical tube containing continuously circulating room temperature water.