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Low velocity impact and compression after impact tests on thin carbon/epoxy laminates

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ABSTRACT

The results of drop-weight impact tests and compression after impact (CAI) tests on carbon/epoxy laminates are presented. The experiments were carried out on specimens of two different geometries (rectangular and circular), according to two ASTM standards. Laminates of small thickness, thus prone to buckling under compression, were considered. Two different quasi-isotropic stacking sequences, obtained by cutting the specimens in two perpendicular directions, were also tested for each geometry, in order to study the influence of both these factors on the impact and post-impact response. In impact tests different dynamic behaviour, energy absorption and material damage were observed between coupons of different geometry; in the case of rectangular coupons, stacking sequence also affected the results. The behaviour of laminates under compression was always characterized by global buckling due to the small thickness. Different deformed shapes of the buckled specimens were observed, depending on geometry and lay-up, also by means of strain measurements. Finite element analysis was helpful in the interpretation of strain recordings in different positions of the laminates. Impact-induced damage did not affect the compressive behaviour and strength in every case, depending on the extent of delamination and the global buckling mode. In some cases the pre-existing damage was able to change the buckling mode and to lower the critical load as well as the ultimate compressive load.

1. Introduction

In order to study the effects of low velocity impact of foreign bodies on Carbon Fibre Reinforced Polymers (CFRP), which still remain an important design issue involving phenomena that are not well understood [1], many researchers have examined results obtained in experimental tests performed on a wide variety of specimen geometries. Consequently, the effect of geometry on impact response of laminates and induced damage becomes a key factor when one tries to compare results found in different conditions, and has already been discussed by several authors, for instance [2–6].

The same also happens in the study of compression after impact (CAI) strength, which has been recognized for many years as the mechanical property suffering the largest reduction with respect to the typical values of the undamaged material [1]. In general, elastic instability is likely to occur during compression tests, especially in the case of thin laminates. Buckling phenomena are strongly dependent on the specimen geometry and size, thus the understanding of the effects of geometrical factors becomes even more important in this field. Many papers regarding the compressive residual strength of impacted laminates are available (for example [7–11]), in which a common concern is to avoid specimen buckling, by means of suitable support, in order to measure load values which do not depend on geometry, but only on the material itself.

It is however felt that, in addition to the work carried out up to now, conditions where buckling actually takes place should also be investigated, because this topic does not seem to have received sufficient attention so far. In slender components, where the compressive strength of the material cannot be reached due to the danger of instability, the possible influence of impact damage on buckling behaviour and strength, together with its dependence on geometry, should be taken into account, as pointed out in [12].

In the present study low velocity impact tests were carried out on coupons of the same thickness but two different geometries, accomplished with support fixtures built according to two ASTM standards [13,14]. CAI tests were then done on specimens of both types, following the specifications of ASTM D7137 [15]; the only significant discrepancy between the specifications and the experiments was the laminate thickness (2.75 mm in the present study, instead of 5 mm), chosen in order to examine the behaviour of thin plates. The aim was to highlight the different impact and post-impact compression response of the two specimen types,

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with particular reference to the interaction between damage propagation, buckling and residual strength.

The adopted experimental conditions led to buckling of the specimens during CAI tests. This occurrence is usually avoided in in-plane compressive testing of laminates. Nevertheless, the present study highlighted several peculiar phenomena of interest, like influence of impact damage on critical buckling load and buckling shape, that can occur only in such conditions. In this way, on the one hand it is shown that the test procedure is not suitable for CAI testing of thin laminates as long as the aim of this kind of experiments is to obtain a compressive strength value that is not affected by instability. On the other hand, the same test method can be properly applied to thin laminates to investigate the compressive behaviour of impact damaged composites undergoing buckling.

2. Experimental method

2.1. Material

The material employed for the tests consisted in 16 ply T300 graphite fibre/epoxy matrix laminates, manufactured from unidirectional prepregs by curing in an autoclave, cut in rectangular specimens 100 mm wide and 150 mm (type A) or 90 mm (type B) long. The average thickness was 2.75 ± 0.05 mm. The values of the in-plane elastic constants of the single ply, supplied by the manufacturer, were as follows: E_1 = 100 GPa, E_2 = 11 GPa, G_{12} = 4.2 GPa, ν_{12} = 0.28.

The stacking sequence of the original laminates was quasi-isotropic $[0/0/90/90/45/-45/45/-45]_S$; two different lay-ups were obtained for the test plates, by cutting them in two orthogonal directions (see schematic in Fig. 1). In half of the specimens the fibres of the external layer were aligned lengthwise, or in the 0° direction (that is parallel to the 150 mm or 90 mm side for type A and B, respectively), thus maintaining the same arrangement of the original laminates. The remaining specimens had a $[90/90/0/0/-45/45/-45/45]_S$ lay-up, with external fibres aligned widthwise (that is parallel to the 100 mm side). From here on, the four types of specimens resulting from all possible combinations of length and stacking sequence will be referred to as A0, A90, B0 and B90, as Fig. 1 shows. Nine coupons were available for each type, a total of 36 coupons being tested.

2.2. Impact tests

An instrumented drop-weight machine [16], shown in Fig. 2, was used to perform low velocity impact tests. A piezoelectric load cell attached to the impactor (whose 12.7 mm diameter hemispherical head is the only part indenting the target laminate), shown in Fig. 2b, allowed the measurement of the contact force history. The actual velocity of the impactor before and after collision was evaluated by a laser device located approximately 30 mm above the specimen surface. An electromagnetic braking system prevented repeated impacts. The signals of both load cell and laser were acquired at 100 kHz sampling frequency without any filtering. The velocity v and the displacement s of the impactor as a function of time were calculated by numerical integration of the contact force history, as suggested in [13], according to the following formulas:

$$v(t) = v_0 + gt - \int_0^t \frac{F(\tau)}{m} d\tau \quad (1)$$

$$s(t) = s_0 + \int_0^t v(\tau) d\tau \quad (2)$$

where F is the measured contact force (obviously zero outside the contact time interval), v_0 and s_0 the velocity and position of the impactor as it passed by the laser device (taken as the initial conditions), m the impactor mass, g the acceleration due to gravity. v and s are intended as positive downwards.

The energy E_a absorbed during impact was also computed from velocity and displacement, following the method proposed in the ASTM code [13]:

$$E_a(t) = m\frac{v_i^2 - v(t)^2}{2} + m\, g(s_i - s(t)) \quad (3)$$

where v_i and s_i are the impactor velocity and displacement at the beginning of contact with the target.

The overall impactor mass was 1.22 ± 0.01 kg; three different drop heights of 0.5, 1.0 and 1.5 m were chosen, corresponding to nominal impact energies of 6, 12 and 18 J respectively. At least two tests were performed at each drop height for every specimen type, and at least two specimens were kept undamaged. Impact-induced damage was examined by visual inspection. Subsequently, all specimens were tested in compression as described below.

Different support fixtures were used for type A and B specimens during drop-weight tests. The configuration used for type A laminates (see Fig. 2c) was compliant with the prescriptions in [13]: the coupon was placed on a rectangular steel base with a 125 by 75 mm rectangular opening, being correctly positioned thanks to three pins and held by four lever clamps with rubber tip. Type B laminates were clamped between two 76 mm internal diameter steel rings, according to [14] (see Fig. 2d). In both cases impact occurred exactly at the centre of the target.

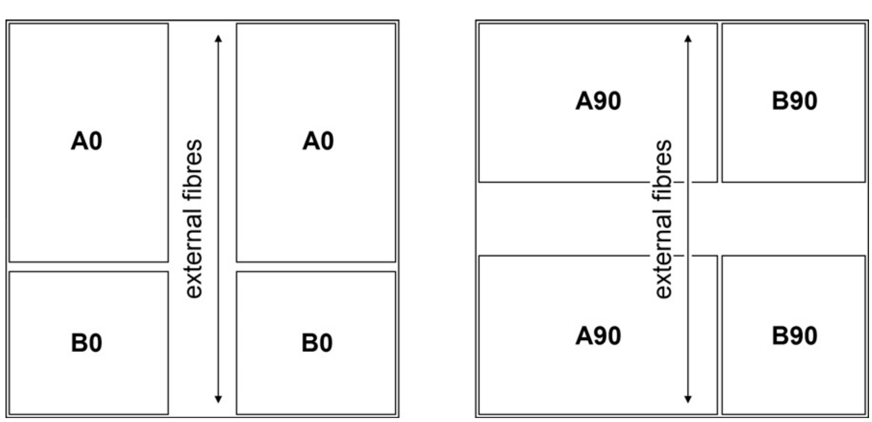

Fig. 1. Schematic of the four types of specimens tested.