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Design of composite materials with improved impact properties

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ABSTRACT

Composites have been widely used in applications where there is a risk of impact, due to the excellent properties these materials display for absorbing impact energy. However, composites during impact situations typically generate an enormous number of small pieces, due to the energy absorption mechanism of these materials, a mechanism which does not include plastic deformation. This can prove dangerous in sports competitions, where the small fragments of the original structure may harm competitors.

This study was designed to explore the possibility of incorporating a material which, whilst maintaining a high level of energy absorption without any plastic deformation mechanism, was able to maintain its original form, or at least significantly reduce the number of pieces generated after impact.

The addition of a polyamide layer, NOMEX®, to a monolithic fabric laminate was investigated in this paper. The process of fabrication is described and the different properties of the material under consideration: interlaminar fracture toughness energy (G_{IC}), indentation (id) and delamination after impact (A_i) and compression after impact (σ_{CAI}), were measured and compared with those of the original monolithic fabric.

1. Introduction

The mechanism by which composite materials absorb energy under impact involves the generation of new surfaces, by breaking the matrix, the fibres and the interphases [1–3]. This powerful means of absorbing energy has the drawback of spreading small fragments of material outside the parts.

In this paper, the introduction of a polyamide [4] to the composite material to reduce the expulsion of material fragments on impact is studied. The idea is to verify whether the polyamide can prevent the dispersion of the composite after breaking.

The polyamide used in this study is NOMEX®, a material derived from aramid and with an internal structure very similar to Kevlar [4–6]. NOMEX® has been investigated for use in the aerospace industry as a core for sandwich composite structures presenting in these cases a honeycomb structure. In this context, tests were carried out to obtain its properties for modelling purposes [7–9] and to see how the number of composite layers affects damage initiation in a laminate under impact [10]. A large difference in surface dent depth was also shown when comparing NOMEX® and aluminium cores in a sandwich composite structure, where NOMEX® presented a very low dent depth [11].

In the current study NOMEX® will be placed in the laminate like any other composite layer, but with the particularity that it is not pre-impregnated. Therefore, the resin required by the NOMEX® layer will be taken from the excess in the carbon fibre pre-pregs. This methodology could slightly alter the amount of resin available for the carbon fabrics (by less than 20%). However, no serious alterations in the internal structure of the material were observed in the micrographs (presence of voids, lack of resin, etc.), due to the excess of resin that the pre-impregnated fabrics have, which now will be used by the NOMEX®, instead of being absorbed by the cork surrounding of the vacuum bag. There is obviously a limit to this solution, as an excess of NOMEX® in relation to the carbon fabric could lead to the presence of imperfections in the material.

In order to check the possible benefits of including NOMEX® in a composite laminate, several tests were completed. All of the following tests were carried out on samples of carbon fibre woven fabric pre-preg (both with NOMEX® and without NOMEX® in order to establish a comparison between the two cases): 5 samples for the tensile strength test, 3 samples for the interlaminar fracture toughness test and 5 samples for the impact and compression after impact tests. The tests chosen were those considered most representative with a view to studying the improvements in the

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properties when including NOMEX®, i.e., interlaminar fracture toughness energy test, impact test and compression after impact test. The tension test was also included to check the behaviour of the laminate under this kind of load.

In the second section of this paper, the material and its manufacturing process are described. In the third section, the tests carried out and the results obtained are presented. In the fourth section the results are analyzed. Finally, the conclusions of this study are presented.

2. Description and manufacturing of the material

The structural materials used in this paper are:

- Woven fabric carbon/epoxy pre-impregnated ply: W3T-282-42-F593-14, with a density of 1442 kg/m^3 [12,13].
- Polyamide: NOMEX® Comfort E502 220i, with a density of 608 kg/m^3 and a thickness of 0.34 mm.

To obtain the test samples, several panels were manufactured, according to [13], some containing just woven fabric and others using both woven fabric and NOMEX®.

In all cases, the stacking sequence was symmetrical and the NOMEX® layer was placed on the plane of symmetry (in the very middle of the lay-up) and was glued to the other layers using the excess resin in the pre-preg, without extra adhesives. The stacking sequence for the tension test is $[(0/90)]_{2s}$, for the interlaminar fracture toughness energy test it is $[(0/90)]_{6s,}$ and for the impact test $[(45/\text{-}45)/(0/90)]_{5s}$. 2 panels of 270 × 90 mm^2 were manufactured for the tension test, 2 panels of 270 × 90 mm^2 for the interlaminar fracture toughness test and 10 panels of 170 × 120 mm^2 for the impact test.

After curing, the panels were cut and inspected with ultrasounds to check that there was no presence of porosity in them. The ultrasonic inspection was carried out with a manual transducer using the pulse-echo technique. The presence of the NOMEX® layer did not alter the inspection, thus validating the manufacturing process.

In order to check that the join between the NOMEX® and the pre-preg was satisfactory, some micrographs [14] were produced (see Fig. 1). Several layers were marked in order to show them clearly. Some of the dark areas that can be identified in the photo appearing in Fig. 1 may correspond to porous areas and others to voids. Their presence does not appear to have a direct influence on the mechanical properties under consideration. Thus, the impregnation of this layer with the resin can be considered to have been carried out properly.

3. Testing and results

The tests made on the samples and their results are presented next. The discussion of the results will be presented in Section 4 of this paper.

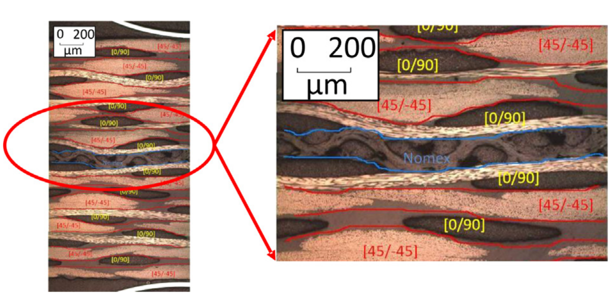

Fig. 1. Micrograph of the composite with NOMEX® (the different layers are detailed).

3.1. Tensile test

The tensile test is used here to calculate the ultimate strength of the material. The tests were carried out using an Instron 4482 universal testing machine, at a speed of 1 mm/min. They were completed following the standard UNE-EN 2561 [15], which specifies that the samples must have the following size: 250 mm (length), 15 mm (width) and 1 mm (thickness). For a proper load transmission, glass fibre tabs were used.

Test results are shown in Table 1. The mean, the maximum and the minimum values of the strength reached in the samples are shown, plus the standard deviation (STD) and the covariance (CV). In the case of the fabric + NOMEX® samples, two results are shown: the stress calculated with the total thickness of the samples (shown between parentheses), and the stress calculated using the thickness of the carbon fabric only, which corresponds to the actual resistant area. The last value is the most important parameter in order to be able to compare the laminate with NOMEX® versus the fabric laminate without NOMEX®, in order to show whether or not NOMEX® damages the original properties.

In all cases, all the ruptures have occurred at the centre of the samples, the separation line between the two final parts being perpendicular to the applied load, as can be appreciated in Fig. 2 for both the samples without NOMEX® (a) and with NOMEX® (b).

3.2. Interlaminar fracture toughness energy test

In this test, the adherence of the NOMEX® to the laminate was checked, measuring the interlaminar fracture toughness energy (G_{IC}).

An Instron 4482 universal testing machine was also used in this test. The objective of the test is to measure the energy needed to propagate a crack throughout the laminate. To this end, the samples are tensioned in the direction of their thickness.

These tests were carried out following the standard AITM 1.0005 [16], which specifies that the samples must have the following size: 250 mm (length), 25 mm (width) and 3 mm (thickness). A demoulding layer has to be placed (during manufacturing) in the middle of the laminate to generate the crack. In the case of the laminate with NOMEX®, the demoulding layer is in contact with one of the faces of the NOMEX® layer, this being the closest configuration to the symmetric one. To obtain a full symmetric configuration would have involved placing the demoulding layer between two NOMEX® layers. However, it would have been very difficult to join these two NOMEX® layers just with the excess of resin from the pre-preg carbon plies.

The crack length to calculate the energy, as stated in the specification, is 100 mm. The test results are shown in Table 2.

3.3. Impact test

The behaviour of the laminate with NOMEX® was compared with the laminate without NOMEX® under impact conditions. In the test, a mass with a semispherical tip falls from a certain height onto the laminate.

The parameters to measure are the perforation depth (i.e., indentation) and the delaminated area.

These tests were carried out in a drop tower following the standard ASTM D7136 [17], which specifies that the samples must have the following size: 150 mm (length), 100 mm (width). The weight of the impactor was 4.47 kg. Note that the ASTM D7136 specifies a value of 5.50 kg for the impactor, but allows the use of other values, the test in this case being designated as a non-standard test.