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Influence of inclined holes on the impact strength of CFRP composites

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ABSTRACT

The objective of this work is to study the effect of inclined holes on the impact strength of carbon-fibre reinforced composites. For this purpose, plates with vertical and inclined holes were tested under low velocity impact and the respective results were compared with control samples without hole. It was observed that inclined holes promote lower maximum loads and higher displacements, which can be justified by the damage mechanisms associated to stress concentration. In fact, the damage becomes asymmetric and increases with hole inclination, as a consequence of change of stress field profile. A complex damage mechanism based on interaction between matrix cracking and delamination was identified. A three-dimensional numerical model based on cohesive zone modelling was developed to deal with damage mechanism and influence of inclined holes. It was concluded that it is crucial to account for matrix cracking to achieve a good prediction of delaminated area. The experimental trends concerning hole inclination were well captured by the model.

1. Introduction

The presence of open holes or cut-outs on composite structural applications is inevitable. In fact, assembling of structural components, access of electric wires or hydraulic pipes require the execution of holes. They promote stress concentration effects leading to complex damage and failure mechanisms occurring during loading process [1]. It is also known [1–3], that the sensitivity of composites to the presence of holes depend on several aspects like material constituents, laminate dimensions, ply orientation, hole size and geometry, and machining quality.

Several authors have been studying the effect of holes on the tensile performance [1–9]. They generally state that holes presence decreases the tensile strength of the laminate, owing to induced stress concentration and different damage mechanisms [1,4–7]. Regarding compressive loads, higher decreases [3,10–15] of strength are reported. Reductions higher than 40% on the compressive strength have been achieved, which is remarkable for carbon fibre/epoxy laminates as consequence of their low compressive strength (60–70% of tensile strength) [13]. The effect of the holes on the fatigue strength [16–21] has also been analysed [16–21]. In general, they concluded that holes have a negligible effect for higher fatigue lives but strongly influence the fatigue performance for lower fatigue lives. Relatively to the out-of-plane loads, and especially in terms of low velocity impact response, literature is less abundant. The majority of the studies available show that damage profile is affected by the presence of holes, confirming a complex failure mechanism characterized by interaction between matrix cracking and delaminations, and a nearly total absence of fibre failure [22–24]. Amaro et al. [25] evaluated the multi-impact response of glass-epoxy composite laminates with open holes. It was observed that the maximum load decreases with the number of impacts, while the displacement at peak load increases. The influence of holes on these parameters is not important for the first impact [22,25], but an increasing cumulative effect is observed with the number of impacts. The presence of holes also increases the energy absorbed by the specimen due to damage occurred and, consequently, affects the impact strength of the laminates. These studies address the influence of vertical holes, i.e., perpendicular to the plate. To the best of authors' knowledge, literature does not report any work about non-vertical holes. Therefore, this work intends to study the effect of inclined holes on the impact strength of composite laminates. This subject is relevant, since the residual properties after low velocity impact can be considerably affected [26–30] and resulting damage is very difficult to detect visually [31,32]. The results will be discussed in terms of load-time, load-displacement and energy-time diagrams,

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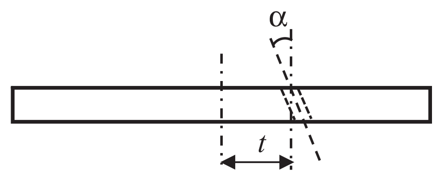

Fig. 1. Geometry of the samples: $t = 10$ mm; $\alpha = 0°$ and 20°.

as well as by the induced damage. Experimental tests on plates with vertical, inclined and without hole (control samples) are described and discussed. A numerical approach based on finite element analysis including cohesive zone modelling was also performed to predict damage for the different cases analysed. The goal is to understand the damage mechanism interaction under low velocity impact and how it is influenced by the interference of hole.

2. Materials and experimental procedure

Composite laminates were prepared from high strength unidirectional carbon prepreg "TEXIPREG® HS 160 REM" (supplied by SEAL, Legnano, Italy) and processed in agreement with the supplier recommendations. They were manufactured with sixteen unidirectional carbon layers with a stacking sequence of $[0_4, 90_4]_s$, using the autoclave/vacuum-bag moulding process. This layup was selected owing to its high mismatch bending between different oriented layers, which is a critical aspect concerning delamination development at those interfaces [27]. The overall dimensions of the plates were $300 \times 300 \times 2.5$ mm^3 and the quality control was performed by C-Scan, to evaluate the eventual presence of defects resulting from manufacturing process. The specimens used in the impact tests were cut from these thin plates with dimensions of $100 \times 100 \times 2.5$ mm^3. Three different configurations were analysed: control samples (without holes), specimens with vertical (0°) and inclined holes (20°) relative to the vertical axis, as shown in Fig. 1. All holes have 4 mm of diameter and they were executed at 10 mm from the plate centre with a special drill for this effect. After drilling, the specimens were evaluated again by C-Scan to verify if any unwanted defect was introduced.

Low-velocity impact tests were performed using a drop weight-testing machine IMATEK-IM10, which is described in [33]. An impactor diameter of 10 mm with a mass of 2.827 kg was used. The tests were performed on square useful section samples of 75 mm × 75 mm by centrally supporting the 100 mm × 100 mm specimens and the impactor stroke at their centre. The impact energy used in the tests was 3 J. This energy was selected, accounting for previous experience of the authors, in order to induce internal damage without promoting perforation of the specimens. After impact tests, the specimens were inspected by C-Scan to evaluate size, shape and position of delaminations. For each condition, three specimens were tested at room temperature (23 °C) and 50% of relative humidity.

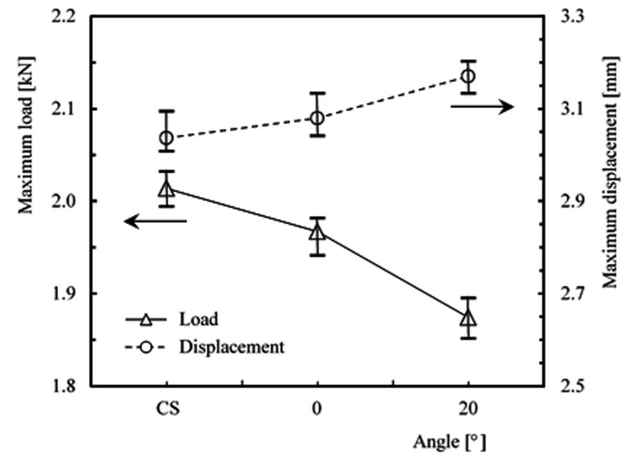

Fig. 3. Maximum impact load and maximum displacement for different hole angles.

3. Results and discussion

The force-time and energy-time curves obtained from the low velocity impact tests on control samples (without holes) and specimens with inclined holes are shown in Fig. 2. These curves are representative of the behaviour verified in all laminates and they reveal the typical profile found in literature [22,25,34,35]. They contain oscillations that can be explained by vibrations of the samples [36,37].

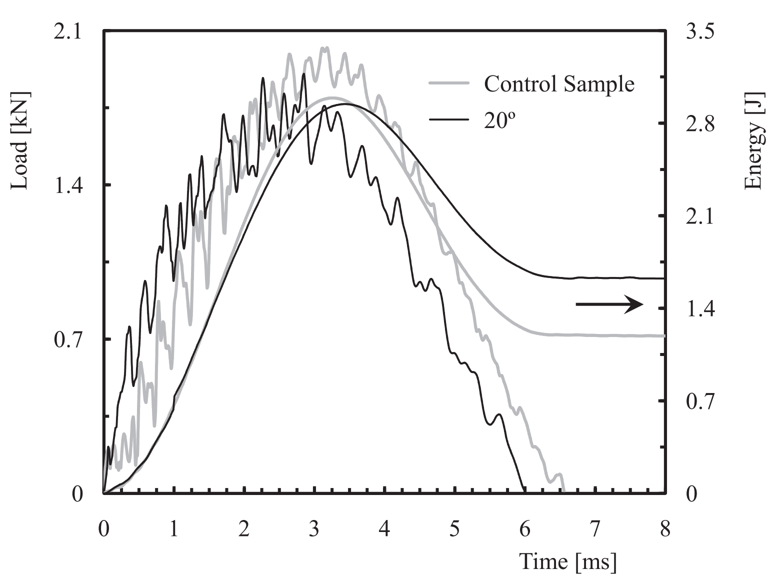

Fig. 2. Typical load-time and energy-time curves for control samples and samples with hole angles of 20°.