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A novel methodology for the assessment of the residual elastic properties in damaged composite components

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ABSTRACT

In the last decades, the use of composite materials for structural components is rapidly increasing. However, damage complexity still represents the main limitation in the further diffusion of structural composites. In this paper, an innovative non-destructive methodology for assessing the amount of damage in composite materials is proposed. The macro energetic variable *Damage Index* is exploited for the prediction of the local residual elastic properties in damaged composites for automotive applications. A strict correlation is found between the predicted and the actual residual elastic properties of the investigated plates. The methodology could thus represent an effective way for guiding the maintenance strategy in structural composite components subjected to damage during service.

1. Introduction

The use of composite materials in different industrial fields (aerospace, automotive and marine) is rapidly increasing. The high specific strength and stiffness and the wide flexibility in shaping and designing are the main advantages in the use of composites. On the other hand, one of the main limitations to their application for structural components is damage complexity. Indeed, differently from metallic materials, composite materials could fail according to several interacting failure modes that induce a rapid and progressive decrement of the mechanical properties, which in many cases can be hardly predicted [1–2]. Therefore, methodologies able to monitor the damage evolution and to predict the residual structural capability of composite materials would permit to extend the diffusion of these innovative materials for structural critical applications.

At present, non-destructive tests (NDTs) are commonly adopted for evaluating the damage level of composite components and structures (see [3–7] for a detailed review on the NDTs currently available). In particular, NDTs are adopted for the quality assessment during the manufacturing process or for the damage analysis of components in service. For instance, optical measuring techniques (shearography [8] and digital shearography technique [9]), computed tomography (in [10] coupled with 3D wavelet analysis), electromagnetic inductors [11], ultrasonic based techniques [6], infrared thermography [6,12] and acoustic emission [13] are commonly used for the identification of defect size, location and orientation and for the individuation of internal non-visible delamination. Vibration based methods [6,14] are instead employed for the damage assessment of component in service, in general together with Finite Element Analysis [15] or wavelet analysis [6,16]. In the latter case (damage assessment of component in service), NDTs could be adopted for the individuation of the proper maintenance strategy: the choice for a specific reparation or for a complete replacement depends on the damage level of the component and on its residual structural capability. In particular, the residual properties of the component in the damaged area are necessary inputs for a correct simulation of the component structural performance in a damaged condition. However, as pointed out in [3], NDTs are currently available to provide information on internal defects originated during the manufacturing process or after a damaging event, but they do not permit a direct evaluation of the local residual properties, thus limiting the use of these materials for critical structural applications.

In the paper, a novel methodology for the quantitative evaluation of the residual elastic properties of damaged laminates is proposed. The macro-energetic damage variable *Damage Index* (*DI*) [17–19] is used for the application of the methodology. The proposed methodology is applied and validated on plate specimens subjected to low velocity impacts.

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2. Materials and methods

A detailed description of the composite material used for the experimental tests is reported in Section 2.1. The experimental activity carried out to validate the proposed methodology is then presented in Section 2.2.

2.1. Materials

A structural composite laminate for automotive application is used for the experimental tests. The composite is made of epoxy resin reinforced by eight twill-2 × 2 carbon fabrics. The first layer is a 380 gsm fabric with 0.45 mm thickness (layer A in Fig. 1) and the remaining seven layers are a 800 gsm fabric with 0.88 mm thickness (layer B in Fig. 1). The laminate can be considered as thick (nominal thickness equal to 6.7 mm) and can be simplified as a symmetric ($\{A_1/B_7\} \approx \{B\}_8 = \{B\}_{4S}$) and balanced ($\{\theta/\theta+90\}_8$) laminate.

Fig. 1 shows a schematic section of the composite laminate used for the experimental tests.

The elastic properties (Young's modulus, shear modulus and Poisson's ratio) and the reference system considered for experimental tests are reported in Fig. 2. Since the investigated composite material is a woven fabric laminate with the same percentage of fiber in direction 1 and 2 (Fig. 2), the mechanical properties and the Poisson's ratio in direction 1 and 2 are necessarily the same (i.e., $E_1 = E_2 = E_{12}$ and $\nu_{12} = \nu_{21}$), as reported in the Figure. Cross-ply $[0/90]_8$ and angle-ply $[-45/+45]_8$ specimens are cut from the manufactured plates. Cross-ply specimens are tensile tested according to the ASTM standard [20] for the evaluation of the Young's modulus of the undamaged composite; similarly, angle-ply specimens are tensile tested according to the ASTM standard [21] in order to assess the shear modulus of the undamaged composite.

2.2. Experimental setup

Quasi-static perforation tests and impact tests are performed on composite plates in order to validate the proposed methodology. Fig. 3 reports the geometry of the plates used for the quasi-static perforation tests (Fig. 3a) and for the impact tests (Fig. 3b).

Quasi-static perforation tests are performed with a servohydraulic testing machine (Instron 8801) to evaluate the perforation

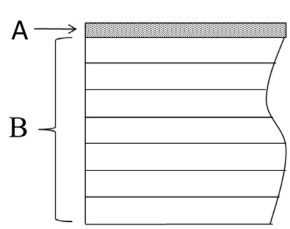

Fig. 1. Schematic section of the investigated composite material.

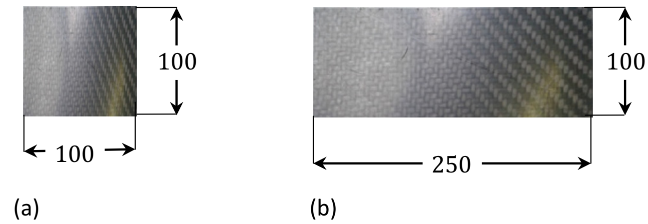

Fig. 3. Geometry of the plates used for the tests: a) quasi-static perforation tests; b) impact tests.

energy and the displacement at perforation. The crosshead speed is set equal to 2 mm/min. A hemispherical tup with diameter 20 mm and a specimen fixture with a circular unclamped region of diameter 76 mm are adopted for the tests, in agreement with the recommendations of the ASTM standard [22]. The tested plates are clamped at both extremity by a mechanical clamping system which ensures an almost uniform clamping pressure all over the clamped area.

Impact tests are carried out using a free-fall drop dart testing machine (CEAST 9350 FRACTOVIS PLUS). The same geometry of tup and fixture used for the quasi-static tests are adopted for the drop dart tests. The impact energy at a given impact velocity is set by varying the impactor mass. The force signal is acquired with a piezoelectric load cell (PCB Piezotronics 203B) mounted near the tip of the impact dart at a sample rate of 1 MHz. The impact velocity, which is controlled by the drop height of the dart, is measured in each test with an optoelectronic device.

Two sets of impact tests are performed. A first set of impacts (*single impact set*) is carried out at five increasing energy levels in order to identify the threshold energy ε_{th}, which is defined as the impact energy that approximately induces less than the 5% reduction of the local elastic properties after the first impact. According to [17–19], a second impact below ε_{th} does not add any further damage to the component. Indeed, as shown in [18], the *DI* computed after repeated low energy impacts is constant impact after impact and the Force vs displacement curve does not change (i.e., the Young's modulus remains constant) with the impact number. Therefore, a second impact below ε_{th} can be considered as non-destructive for the laminate. In order to increase the signal to noise ratio in the *DI* computation and to reduce inaccuracy in the computed *DI* values, second impacts will be performed exactly at ε_{th}.

Table 1 reports impact velocity, impactor mass and impact energy considered for the first set of impact tests. For each case, seven repetitions are performed.

The residual elastic properties of the damaged plates are experimentally measured in order to compute the ε_{th} value. Strips with width 20 mm are cut from the impacted plates around the damaged area so to obtain specimens for performing tensile tests, according to the ASTM standards [20,21]. Nine and eighteen specimens are cut to assess the residual Young's modulus and residual shear modulus, respectively.

- $E_1 = E_2 = E_{12} = 54\ GPa$
- $G_{12} = \frac{E_{12} \cdot E_{XY}}{2 \cdot (2 \cdot E_{12} + E_{XY} \cdot (\nu_{12} - 1))} = 3.5\ GPa$
- $\nu_{12} = \nu_{21} = 0.08$

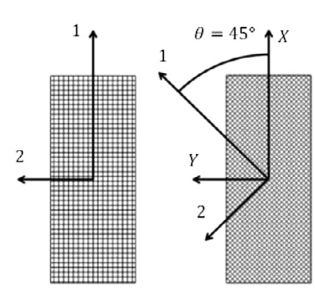

Fig. 2. Mechanical properties of the undamaged laminate and reference system.