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Composite material components damaged by impact loading: a methodology for the assessment of their residual elastic properties

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ABSTRACT

Purpose: Detection and evaluation of damage due to impact or fatigue loading in components made by composite materials is one of the main concern for automotive engineers. We focus on damage due to impact loading on long fibre, plastic matrix composite, as they represent one of the most interesting development solution for automotive components toward lightweight structure that in turn means reduction of fuel consumption and of Green House Gas emissions.

Design/methodology/approach: An innovative simplified methodology is proposed, based on the impact and repeated impact behaviour of composite material, for the evaluation of the induced damage and of material residual elastic properties. The investigated composite laminate is made of eight twill-wave carbon fabrics impregnated with epoxy resin.

The methodology consists of two phases: at first the identification of the impact response. Composite plates have been impacted at different energy levels and residual elastic properties measured through standard tensile tests. The relationship between impact energy and residual elastic properties is obtained. Then the exploration impact load is identified, large enough to give a well-defined picture of the suffered damage but soft enough to do not induce further damage in the composite laminate.

Findings: This exploration impact test and the Damage Index (DI) value, as interpretation key, leads to a prediction of the local residual elastic properties in the damaged area.

The proposed methodology has been validated on plate specimens. A strict correlation is found between the predicted and the actual residual elastic properties of the damaged composite plate.

Practical implications: Subsequently it has been applied to a composite beam, with a omega shape transverse section, that can be considered as a demonstrator for a typical beam used in the car body frame.

Originality/value: A selection on the following alternatives will be possible: a – don't care the damage is not affecting the structure performance; b – repair is needed but will be sufficient; c – substitute the damaged component as soon as possible.

Keywords: Composite materials, NDT, Impact loading, Damage Index, Residual elastic properties

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METHODOLOGY OF RESEARCH

1. Introduction

In order to fulfil the strict limitations imposed by international regulations related to fuel consumption and Green House Gas (GHG) emissions, researchers and designers in the automotive field are making great efforts to lighten vehicles and enhance their environmental sustainability.

In view of a lightweight design of vehicles, composite materials represent one of the most promising alternatives to typical metallic materials for many automotive components. However, the damage complexity in composite materials strongly limits their diffusion in the field: before final failure, composite components suffer different and, often, interacting failure modes [1] that may be hard to predict through numerical simulation or even to monitor. In this respect, a reliable but simplified damage assessment and evaluation procedure, made suitable for in field applications, would permit a larger use of composites for structural automotive components.

As discussed in papers [1,2], two different types of defects can be considered: defects due to the manufacturing process and defects caused by in service loads, mainly as a consequence of fatigue or impact loading. The paper concentrates on the second type of defects.

At present, non-destructive tests (NDTs) are widely adopted for a qualitative damage assessment of composite components and structures [2-5]. In the review paper [2], a number of different NDT techniques are presented and discussed in brief: the techniques range from methods based on vibration analysis, strain monitoring, ultrasonic inspections, acoustic emissions, microwave inspections, spectroscopy, and infrared thermography, optical interferometry, to radiographic and radioscopic inspections. In [3], authors are presenting and discussing the possibility of detection and analysis of impact damage through ultrasonic testing, optical thermography and sonic infrared methodologies. Particular attention is posed on barely visible impact damage (BVID). In [5], damage detection, localisation and quantification are assessed using a technique based on the analysis of the vibration response, in particular of the inheritance FRF plot.

All the above techniques are generally suitable for applications into specifically equipped experimental laboratories.

An interesting work is the one presented in paper [4], where authors develop the study of damage identification in airplane structures through different techniques, such as those based on piezoelectric transducers, on MEMS accelerometers and on fibre Bragg grating sensors. All the proposed techniques are very effective, but require the embedment into the structure of specific sensors during manufacturing.

Our goal is to develop a testing methodology that can provide quantitative information on damage extension and yet which is suitable to be utilized in a repairing shop on real parts (not only on material coupons), without requiring highly sophisticated testing instrumentations. In other words, we are looking for methodologies that could be exploited to effectively guide engineers in the selection of the optimal maintenance strategy. The decision as to whether a component needs or not repair, and whether to opt for specific repair or replacement, depends on the residual structural capability of the damaged component in performing its mission. The NDT could provide the required pieces of information for taking the final decision.

In particular, a NDT that provides a quantitative assessment of the local residual properties of the damaged component would offer the necessary input for addressing the proper maintenance strategy. Simulation results would then suggest the proper maintenance strategy. However, as reported in [2-4], the available NDTs provide useful information on internal defects, either generated during the manufacturing process or after a damaging event, but do not permit a direct assessment of local residual properties.

The objective of the present study is to take the first steps towards a simplified NDT for the quantitative evaluation of the residual elastic properties in damaged composites. An innovative simplified methodology is proposed for the detection and evaluation of the relevance of the sustained damage, in terms of residual elastic properties. The methodology makes use of the macro-energetic damage variable Damage Index (DI) [6-8].

The proposed methodology is first tested and validated on plate specimens. The second case study of a composite beam, which is representative of a typical component used in the car body frame, confirms the validity of the proposed approach.

2. Materials and methods

The composite laminate investigated in the preliminary test phase was made of epoxy resin reinforced through eight twill-2x2 carbon fabrics. The manufacturing procedure consisted of vacuum bagging and autoclave curing. The first layer was made of a 380 gsm fabric with a 0.45 mm thickness, while the remaining seven layers were made of 800 gsm fabrics with a 0.88 mm thickness. The tested composite laminate represents the material used in the manufacturing of a real automotive part. The first layer contains less carbon fibre reinforcement to improve the aesthetics of the exterior surface of the part. The laminate can be considered a thick laminate, since the nominal laminate thickness is 6.7 mm.

Cross-ply $[0/90]_8$ and angle-ply $[-45/+45]_8$ specimens were cut from the manufactured plates. Cross-ply specimens were tensile tested according to the relevant ASTM standard [9] for evaluating the Young's modulus of the undamaged composite; angle-ply specimens were tensile tested according to the relevant ASTM standard [10] for evaluating the shear modulus of the undamaged composite.

The proposed methodology consists of two phases: the assessment of residual elastic properties after impact and the identification of a model for the prediction of the residual elastic properties through NDTs.

Within the first phase, a first set of impact tests was carried out. Composite plates were impacted according to the relevant ASTM standard [11] at five different energy levels (30 J, 40 J, 50 J, 90 J and 150 J). In order to evaluate the residual elastic properties of the damaged plates, the plates were cut around the impacted area to provide specimens for the tensile tests. Tensile tests were then performed on the damaged specimens, according to the ASTM standards [9,10]. At the end of the first phase, the relationship between the impact energy and the residual elastic properties was obtained.

The identification of this relationship also permitted to evaluate a threshold energy (E_{th}). This threshold energy was set at the impact energy that approximately induces a 5% reduction of the local elastic properties in the damaged laminate. A 5% percent reduction was selected so to have a significant representation of the damage relevance and extension and yet not to induce substantial damage in the composite laminate. The damage introduced into the laminate when impacted at E_{th} is indeed negligible when compared to the damage caused in the subsequent impacts at greater energies. Therefore impacts at E_{th} can, in our opinion, be considered as NDTs and can be exploited for the non-destructive damage assessment of the laminate.

Within the second phase, a second set of impact tests was carried out. A new set of composite plates was initially impacted at five energy levels (20 J, 50 J, 80 J, 110 J and 140 J), and then impacted again on the damaged area at E_{th} to assess the damage sustained by the specimen during the first damaging impact. In particular, the second non-damaging impact at E_{th}, allowed the computation of a macro-energetic parameter, called the detecting Damage Index (DI_d). This Index is a refinement of the more general Damage Index (DI) introduced in the papers [6-8] to describe the energy balance during both the penetration and the perforation phases, characteristic of impact testing on plates. The detecting Damage Index is calculated based on the equation:

$$DI_d = \frac{E_a}{E_{th}} \cdot \frac{s_{MAX}}{s_{QS}} = \begin{cases} \cong 0 \ (undamaged) \\ 1 \ \ (perforated) \end{cases}, \tag{1}$$

where s_{MAX} is the maximum displacement achieved during the impact, s_{QS} is the perforation displacement in a quasi-static test and E_a denotes the absorbed energy (Fig. 1). The value of the displacement is obtained through double integration of the load signal with respect to time.

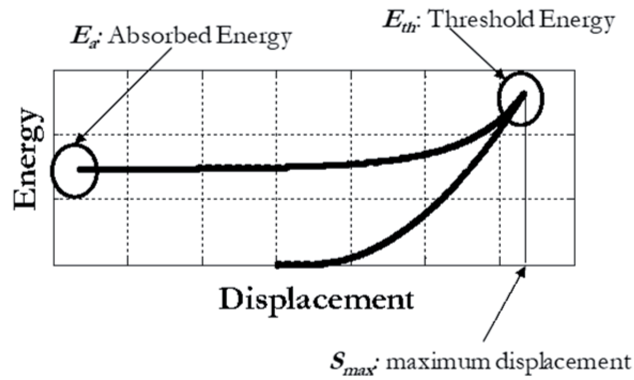


Fig. 1. Energy-displacement diagram: relevant quantities for the computation of the detecting Damage Index

Figure 1 shows a representative experimental result of an impact test, where the adopted impact energy is equal to the threshold energy E_{th}. In particular, the diagram of figure

1 shows the relationship between the energy and the displacement. The potential energy is progressively transformed into plate deformation energy up to the peak visible on the right end side of the diagram. The displacement increases with time and reaches its maximum value, s_{max}, whose value depends on the given testing conditions. Finally, since the test is performed at low impact energy, the dart rebounds and some of the deformation energy (the elastic part) is given back. At the end of the rebound phase, when the displacement returns to zero, the residual value E_a we can read on the vertical axis represents the energy that has not been restored but was absorbed during the test. The parameter s_{QS} is the displacement that can be measured during a Quasi Static (QS) perforation test, i.e. when the dart perforates the composite material plate. This quantity provides a reference measure of the plate deformation at failure in the quasi-static loading conditions.

3. Results and validation: specimens

The relationship between the residual elastic properties and the impact energy was identified in the first set of tests and the threshold energy E_{th} fixed at 6 J. Within the second phase, the DI_d values obtained from the NDT impacts at E_{th} were correlated to the impact energies adopted for the subsequent damaging impacts (i.e., 20 J, 50 J, 80J, 110 J and 140 J). Therefore, for any given impact energy, the residual elastic properties and the DI_d value derive from the damaging and the NDTs impact respectively. Finally, through the impact energy, an indirect correlation was estimated between the DI_d value and the residual elastic properties of the impacted laminate (Fig. 2).

As shown in Figure 3, for each investigated elastic property a regression model can be used to identify the relationship between the DI_d and the given residual elastic property.

In particular, a simple linear model fits the residual Young's modulus, while a quadratic model was adopted for the shear modulus. The least square models are in good agreement with the experimental data. The correlation coefficient R^2 is, in both cases, larger than 0.98.

At last, an experimental validation of the fitted models was carried out. Composite plates subject to the second set of impact tests were cut around the damaged area and then tensile tested to experimentally evaluate the residual elastic properties. Figure 4 shows the graphs of the predicted residual properties with respect to the experimental elastic properties.

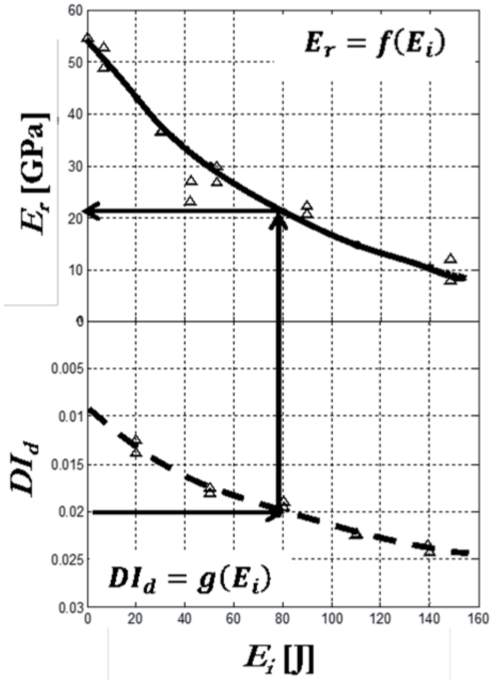


Fig. 2. Example of indirect correlation between the measured residual elastic modulus and the DI_d values

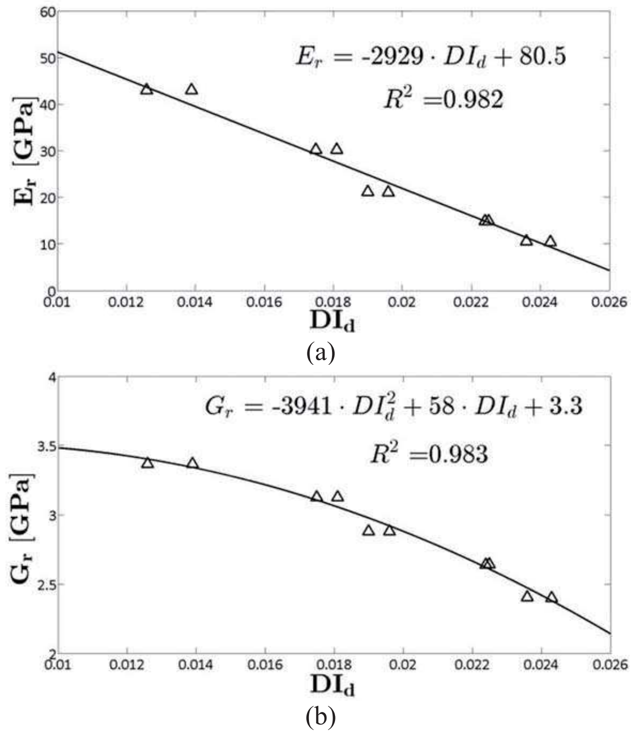
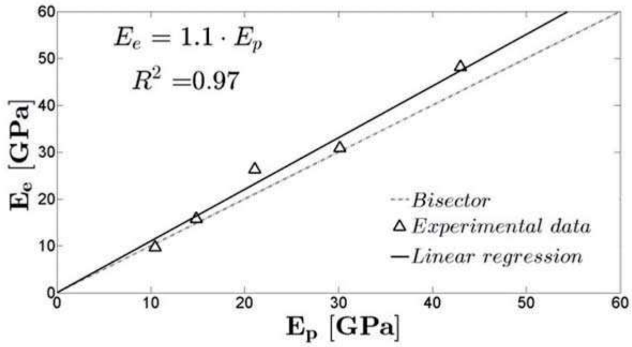
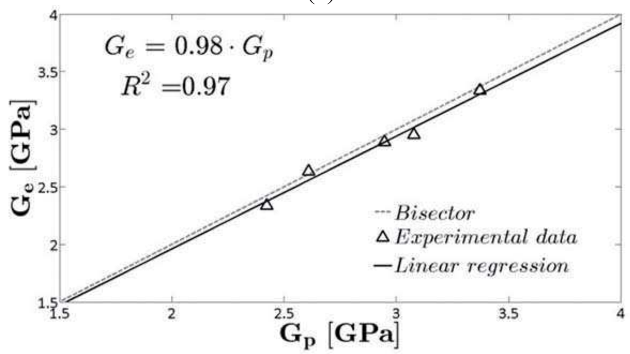


Fig. 3. Test data and the related regression models for the residual property vs. DI_d: a) Young's modulus, b) shear modulus

As shown in Figure 4, the predicted residual moduli are in good agreement with the residual experimental moduli. Large values of the correlation coefficients, that approach 1, and small differences in slope between regression functions and bisectors highlight the effectiveness of the proposed methodology.



(a)



(b)

Fig. 4. Experimental validation of the proposed methodology: a) Young's modulus, b) shear modulus

4. Results and validation: components

The structural composite component investigated in this study is a simplified automotive rocker beam, commonly named 'brancardo' (Fig. 5). It is an open section omega shaped beam, that is representative of the external part of a rocker beam. The real rocker beam has a closed section. However, in consideration of the wall thickness, it is expected that the local bending stiffness is large enough to make the simplified beam representative of the real structure. The composite used for the 'brancardo' is the same material of the investigated composite plates.

The rocker beam was subject to impact tests, using a drop dart testing machine, where the standard dart impactor was modified in order to span over the whole transverse section of the beam. The beam was fully supported on a flat rigid plate so that the impact loading caused a local damage.

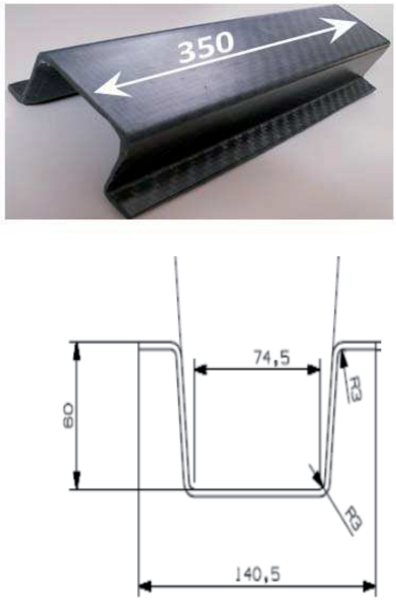


Fig. 5. Simplified automotive 'brancardo'

Figure 6 shows a picture of the beam after the impact test. The permanent local deformation of the material at the impact zone is clearly visible.

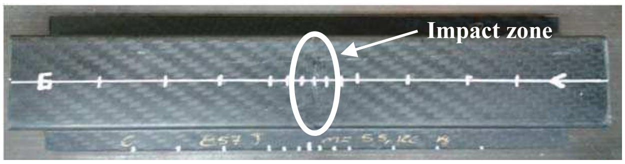


Fig. 6. Picture of the impacted component and identification of the 13 evaluation points for the validation

As shown in Figure 6, thirteen different points were identified along the impacted beam. The points are located symmetrically with respect to the impact section and progressively spanned along the beam axis, with a fine spacing close to the impact section and a coarse spacing outside the impact zone. At each evaluation point, a further impact test was performed at E_{th} to compute the local DI_d value. The local residual Young's moduli were finally estimated for each evaluation point according to the models reported in Figure 3.

A tensile specimen was cut from the impacted beam and a standard tensile test was performed to measure the local residual Young's modulus at each evaluation point. Figure 7 shows the comparison between the actual and the estimated residual Young's moduli.

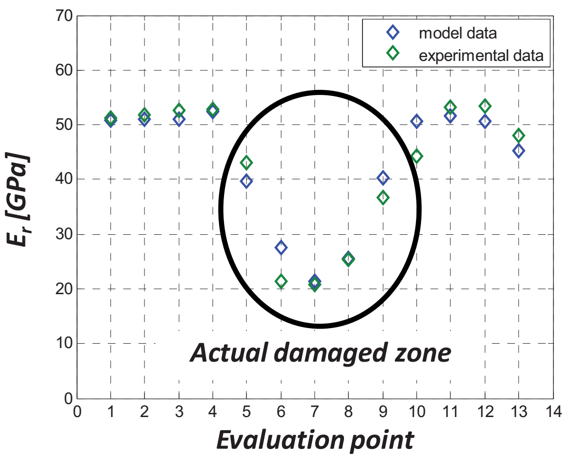


Fig. 7. Trend of the residual Young's modulus along the impacted component. Comparison between estimated and actual values

5. Conclusions

An innovative methodology for the assessment of the residual elastic properties in damaged thick composites is proposed in the paper. The methodology is based on data that can be derived from a non-destructive impact test and on the relationship that can be drawn between such data and the material residual properties. In particular, a macro-energetic parameter, the detecting Damage Index (DI_d), is computed after non-destructive impacts and it is used for predicting the residual elastic properties of damaged composite laminates.

One of the key points of the methodology is the material characterization that serves to identify the relationship between the value of the impact response parameter, the Damage Index (*DI*), and the material residual properties. Hence, a preliminary material characterization was carried out on plates made of a composite material that is typically used for automotive applications. A good correlation was found between the *DI* and the residual elastic properties of the impacted laminates. This result constitutes the base for the further step: the use of the DI_d to predict effectively the local residual elastic properties of the damaged laminate.

Following the initial validation on damaged composite plates, the proposed methodology was subsequently applied to a composite beam that is assumed to be representative of a structural component of the automotive body. Also in this more realistic case, the predicted and actual values for the local residual elastic properties were found in good agreement.

Thanks to the proposed methodology, after a preliminary laboratory characterization that serves to identify the correlation between the *DI* and the residual elastic properties, the level of damage in the composite and the local residual elastic properties could be effectively estimated from the DI_d values measured through NDTs performed on the damaged components.

One advantage of the proposed methodology is the possibility to adopt it on real parts (not only on material coupons) at the repairing shop, with no need for highly sophisticated testing instrumentations. Knowledge of the level of damage after damaging events could effectively guide engineers in the selection of the optimal maintenance strategy: a) do not repair. The level of damage is not affecting the performance of the structure; b) repair. Damage has deteriorated, although locally, the performance of the structure; c) substitute. Extent of damage is relevant and the part is no longer able to endure the characteristic service loads.

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