# Structural performance analysis of smart carbon fiber samples supported by experimental investigation

M. Viscardi, M. Arena, G. Barra and L. Guadagno

***Abstract*—** The use of composite materials has grown significantly in recent years thanks to new manufacturing processes, which have allowed for competing of laminates with metal alloys in in a broad spectrum of technological applications. As known, a composite is a material made by joining two or more constituents, therefore key concept is to combine more performances in a single final product. For their peculiarities, such as the heterogeneity and anisotropy, composites are materials used as a solution to problems of different areas, taking advantage of lightweight, strength, stiffness, good behavior to fatigue and corrosion and reduced manufacturing costs. Precisely because of their complex nature, the execution into a potential industrialization stage pose to the designer new problems but also targets, dictated by the technical need to clearly characterize both the macroscopic that the microscopic properties. The main goal of this activity has been to assess the mechanical properties of two carbon fiber/epoxy samples by means of experimental tests and numerical simulations with a very good correlation level. The outcomes achieved and described in this paper have been performed within an ambitious research project focused on the development and application of self-healing materials: one of the specimens in fact was filled with microcapsules to trigger the self-repair process in case of damage. Among the significant advantages of these smart materials, the improved ability to dissipate vibration energy has been especially appreciated in this framework. The conducted tests have revealed a higher damping coefficient compared to that one of a standard CFRC. Relying upon the validated FEM, sensitivity nonlinear analyses were carried out to evaluate the stiffness trend with respect to first-ply failure.

***Keywords*—** Damping, Failure analysis, Finite Element Model, Laminate, Smart material, Self-healing.

## I. INTRODUCTION

THE search for lighter materials and more easily integrated into large-scale assembly procedures is leading the industrial sectors towards the use of composite materials. Just think that the best-known aircraft (Boeing 787), automotive (Ferrari Enzo, Lamborghini Avendador, Alfa Romeo 4C, BMW I3) and railway industries are marketing from several years fully laminated models. The increasingly dominant role of lightweight materials in transport engineering is motivated by the multitude of benefits that they could offer like the weight optimization and the reduction of the fuel burn and noise levels [1]. Due to these peculiarities, composite materials are used for a long time in many other technological sectors aimed at solving problems with different needs, not structural only, such as those in the civil, sports and biomechanics. The use of such materials involves the exploitation of many advantages such as lightness, strength, rigidity, good behavior to fatigue, ability to design the material according to its own need but also cost reduction of manufacturing, weight and joints. The main disadvantage, especially for long-fiber materials, is the cost, and from a mechanical point of view, the fracture behavior, which is typically brittle. Due to the higher complexity with respect to conventional solution based on metal alloys, it is necessary characterize both the macroscopic that the microscopic properties in perspective of potential certification and industrialization processes. The presented study is part of an ambitious research project focused on the development and application of self-healing materials: one of the specimens in fact was filled with microcapsules to trigger the self-repair process in case of damage. The self-repair function of composites made of 2D laminates, is based on the metathesis polymerization of a healing agent based on the blend of two olefins (ENB/DCPD blend) activated by Hoveyda-Grubbs' 1st generation catalyst [2]. The self-healing resin has been infused into a carbon fiber dry preform using an unconventional bulk film infusion technique (24 plies of carbon fiber cloths (SIGMATEX (UK) LDT 193GSM (grams square meter) /PW (plain wave) /HTA40 E13 3K (3000 fibers each tow). A thick wet film of resin has been placed under the carbon preform, under vacuum bag, without any tube connection with external reservoirs, so that the resin is forced through the shortest possible path for infiltration, reducing at the minimum the necessary time and filtering problem [3]-[4]. An assessment of structural properties of two carbon fiber/epoxy coupons has been carried out by experimental tests conducted in the laboratory of Department of Industrial Engineering (Aerospace Section, Università degli Studi di Napoli "Federico II"), Fig. 1.

Fig. 1 Coupons extracted for testing activity

In the first part of such paper, both static that dynamic results of experimental tests on the specimens are described and discussed. Subsequently, starting from them, a special attention has been given by the authors to the set-up of a well-correlated numerical model. Thanks to the reliability of this one, sensitivity nonlinear analyses were performed within the MSC Nastran® environment to preliminarily estimate the load-displacement curve with respect to first-ply failure. Such rational approach has allowed for the highlighting the inaccuracy of an only linear resolution to deepen the structural behavior especially in the case of innovative composite materials.

## II. EXPERIMENTAL TESTS

The experimental measurements performed within such research have allowed for estimating both the static that the dynamic properties of innovative composite specimens with different treatments.

### A. *Static stiffness*

In this section, the results of laboratory tests in order to measure the flexural stiffness coefficient (1) will be explained.

$$k = \frac{F}{w} \tag{1}$$

The static stiffness of each composite sample has been evaluated in correspondence of several load settings by means of a test facility, shown in Fig. 2, 3. A strong-back constraint has been adopted for the correct mounting of the specimen to the test-rig while the deformation has been measured to the free tip by means of a distance amplifying instrument. In Fig. 4 the trends of load versus static displacement have been plotted with reference to each case of investigation.

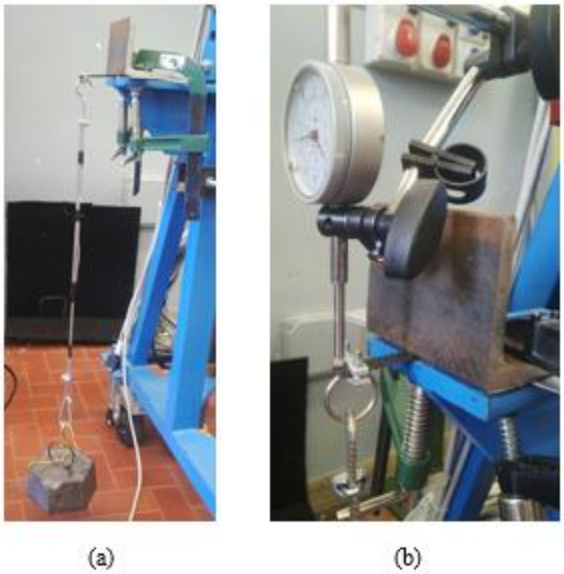

Fig. 2 Static test: load application (a), analog micro-meter (b)

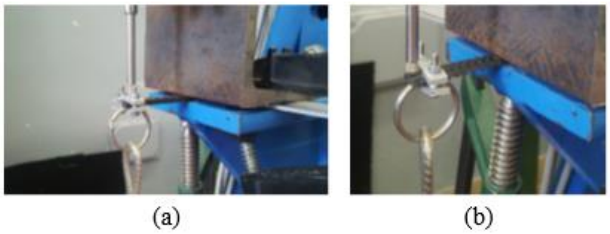

Fig. 3 Specimens tested: sample G (a), sample SH1 (b)

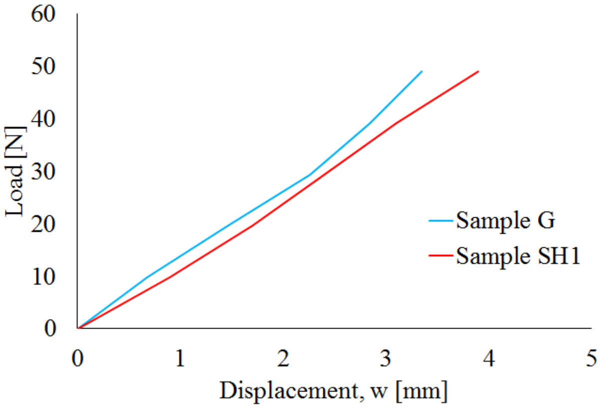

Fig. 4 Flexural static test, load-displacement curve

The results, listed in Table I, show Sample SH1, because of its smaller thickness, is slightly less rigid with a bending load.

Table I Static stiffness estimation

| ID coupon | Average k [N/mm] |
|---|---|
| Sample G | 14.45 |
| Sample SH1 | 13.25 |

### B. *Spectral testing*

On the structural system, two monitoring points have been defined for the mode shape reconstruction by a hammer testing. The structure response has been measured by piezoelectric accelerometer while the excitation force by piezoelectric load cell (SISO, Single Input Single Output method) in the spectral range [0; 1024 Hz] [1]. The transfer function has been acquired during the test by LMS Acquisition and Analysis System®, Fig. 5. In order to simulate the fixed-free condition, the prototype has been clamped in the jaw of a static test machine, Fig. 6.

Fig. 5 Dynamic contact test instrumentation

(a) (b)

Fig. 6 Test set-up: Sample G (a), Sample SH1 (b)

### C. *Modal damping*

Good quality experimental data were obtained, as demonstrated by the consistency of the coherence and FRF (Frequency Response Function) functions. The Fig. 7 compares the frequency responses (FRF) of the tested materials. In Fig. 8, the first elastic mode shape of the fixed-free specimen is represented.

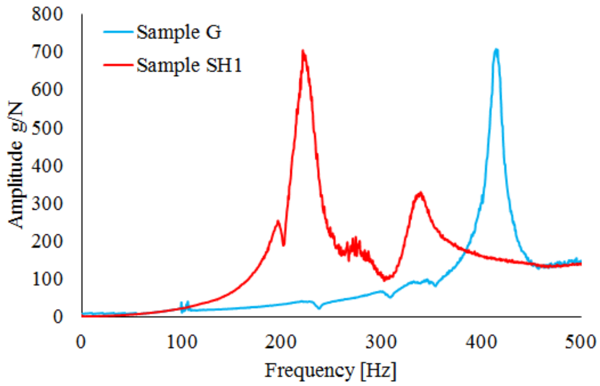

Fig. 7 Frequency Response Function (FRF)

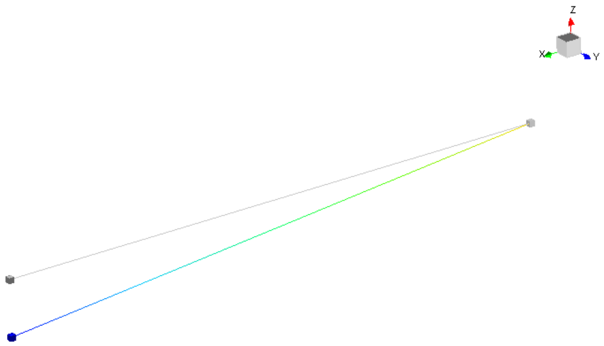

Fig. 8 First flexural mode shape

The results processing leads to observe a significant enlargement of the resonance peak mainly due to the Sample SH1 specimen. The greater flexibility is perceived as a shift of the transfer function curve in virtue of (2).

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{2}$$

The half-power bandwidth method (HPB) is very suitable to evaluate the modal damping factor ζ from frequency domain close to the resonance region: two point corresponding to 3 dB down from the resonance peak are considered for the calculation of (3).

$$\zeta = \frac{f_2 - f_1}{f_n} \tag{3}$$

Where $f_1$ and $f_2$ represent the cut-off frequencies at the two points with an amplitude of 3 dB under the resonance value, $f_n$ is the value of the natural frequency [1], [20]. In Table II the damping coefficients, obtained by such method are reported.

Table II Modal damping coefficients, HPB

| | **Sample G** | **Sample SH1** |
|---|---|---|
| $f_n$ [Hz] | 415 | 221.5 |
| $A_{MAX}$ [g/N] | 676.34 | 702.34 |
| Modal damping, $\zeta$ | 1.73% | 5.00% |

### D. *Time domain response*

The maximum level of response for each resonance frequency is obtained immediately after the impact, while the amplitude decays thereafter at a speed proportional to the structural damping factor ξ, which can be calculated according to the relationship (4) in time domain, Fig. 9.

$$\xi = \frac{\delta}{\sqrt{\delta^2 + 4\pi^2}} \tag{4}$$

In which δ is the logarithmic decrement (LD) calculated between two consecutive peaks, $g_i$ and $g_{i+1}$, of the acceleration time history (5) [1], [20].

$$\delta = \ln\left(\frac{g_i}{g_{i+1}}\right) \tag{5}$$

In Table III the damping coefficients, obtained by that method are reported.

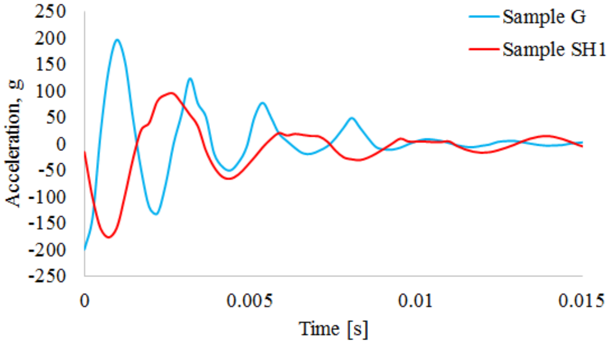

Fig. 9 Response time history

Table III Structural damping coefficients, LD

| | Sample G | Sample SH1 |
|---|---|---|
| LD, $\delta$ | 1.629 | 0.470 |
| Damping ratio, $\xi$ | 1.178% | 3.967% |

## III. STRUCTURAL NUMERICAL MODEL

A FEM (Finite Element Model) analysis has been performed in order to correlate both the modal response that the static displacements of the specimens: the results are very congruent with the ones coming from the experimental tests. Furthermore, the nonlinear material properties at first-ply failure has been investigated by means of an advanced implicit solver (SOL 400) within the MSC Nastran® environment [5]. Such rational approach has allowed for the highlighting the inaccuracy of an only linear resolution to deepen the structural behavior especially in the case of innovative composite materials [6]. Each coupon has been discretized by 2-D (CQUAD) mesh with cross-ply orthotropic properties within Patran® software, Fig. 10 [2].

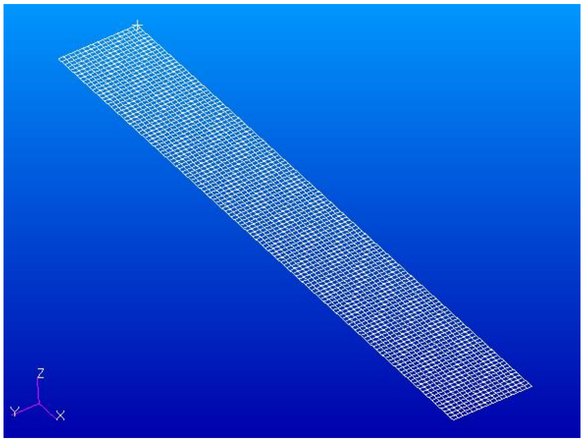

Fig. 10 Structural system mesh

In this section, the strategies adopted in order to validate the numerical model both from static that dynamic standpoint are described.

### A. *FEA results: linear static analysis*

The static analysis in elastic range were carried out in the hypothesis of base perfectly clamped and with a concentrated load at the free edge. For a better distribution to the nodes close to the force application point, a rigid element RBE2 [6] has been created, Fig 11. Starting from the same load cases used for the test, it has been determined the load-displacement curve, Fig. 12-13.

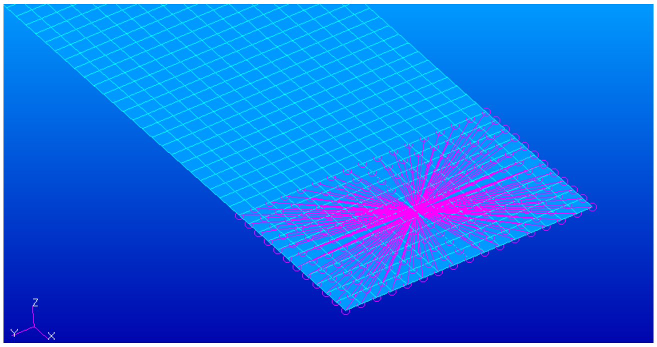

Fig. 11 FE detail for load application

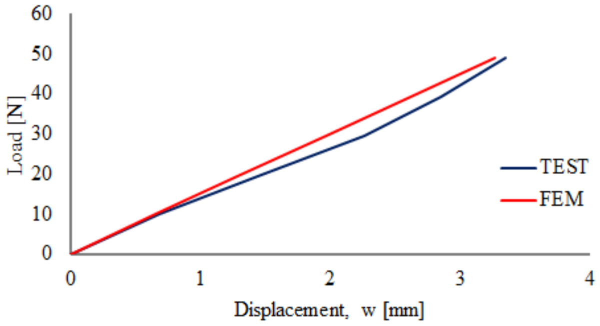

Fig. 12 Linear static analysis, Sample G

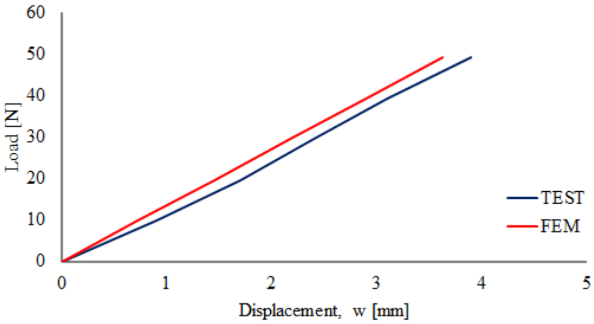

Fig. 13 Linear static analysis, Sample SH1

### B. *FEA results: frequency domain analysis*

Within the numerical modal analysis context, particular attention has been given to the simulation of the real mass of each specimen: therefore, the masses respectively of the first coupon (2.5 grams) and second one (1.6 grams) have been successfully simulated. For the purpose to evaluate the resonant frequencies properly tuned on the same values of the experimental tests, it was necessary to take into account the acceleration sensor mass, which is not negligible (1.9 grams). In this regard, a CONM2 lumped mass has been set in the master node of the RBE2 [6]. The figures below, Fig 14-15, show the mode shapes of the two specimens. The natural frequencies are very close to those experimentally measured, Table IV.

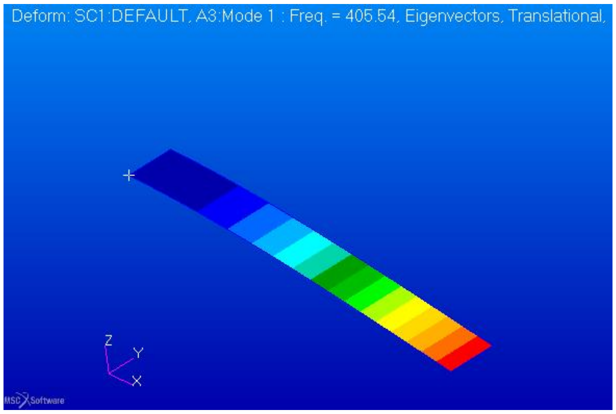

Fig. 14 Modal analysis, Sample G

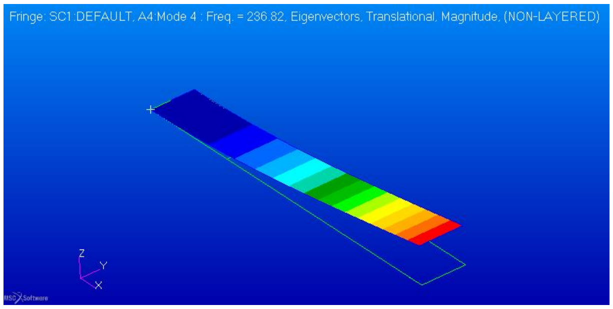

Fig. 15 Modal analysis, Sample SH1

Table IV Natural frequencies correlation

| | **Sample G** | **Sample SH1** |
|---|---|---|
| LMS TestLab® | 415 | 221.5 |
| MSC Nastran® | 405.540 | 236.820 |
| Deviation (%) | 2.28% | 6.47% |

### C. *Failure analysis*

Starting from the allowable values of the material used for the finite elements simulations, Table V, it has been estimated in a preliminary way the strength at which the first-ply failure occurs by the Tsai-Wu failure criterion. It should be taken into account that in a laminate, failure mechanisms are more complicated; hence, a lamina failure criterion must be flexible enough to accommodate the more complicated nature of laminate analysis. Presented study gives emphasis to the effect of nonlinearity on the failure initiation and progression. Inter-laminar failure is not considered since most inter-laminar failures are modelled by fracture mechanics based approach [13]. However, the delamination can also be predicted by using strength or strain based failure criteria. These criteria predict the failure load by using a single quadratic or higher order polynomial equation involving all stress or strain components. Their origins go back to von Mises distortional energy yield criterion for ductile metals, which was adapted to account for anisotropy in ductile metals. Failure is assumed when the equation is satisfied and if the failure index is higher than one. An interaction term in the polynomial equation is present [16]-[19]. The Tsai-Wu criterion predicts failure when the failure index in a laminate is equal to the unit, Table VI (6).

$$FI = \begin{matrix} F_1\sigma_x + F_2\sigma_y \\ + \\ F_{11}\sigma_x^2 + F_{22}\sigma_y^2 + F_{66}\tau_{xy}^2 \\ + \\ 2F_{12}\sigma_x\sigma_y \end{matrix} \qquad (6)$$

Table V Material allowable values

| | |
|---|---|
| **$\sigma_{xt}$ (MPa)** | 2138.48 |
| **$\sigma_{xc}$ (MPa)** | 1470 |
| **$\sigma_{yt}$ (MPa)** | 76 |
| **$\sigma_{yc}$ (MPa)** | 250 |
| **$\tau_{xy}$ (MPa)** | 60 |

Table VI Failure Index estimation, Tsai-Wu

| | **Load [N]** | **Failure Index** |
|---|---|---|

| | | |
|---|---|---|
| **Sample G** | 196.2 | 1.396 |
| **Sample SH1** | 147.15 | 1.549 |

### D. *Nonlinear static analysis*

Two dimensional finite element based gradual failure analysis method has been used to study first-ply failure of the models under in-plane geometrically nonlinear deformations [8]. In the gradual failure analysis of structures, geometric nonlinear effects become prominent when the structure is subjected to large displacements and/or rotations. Follower force effect due to a change in load as a function of displacement and rotation is one aspect of geometric nonlinearity that must also be taken into account especially when out-of-plane loads resulting in large deformations are applied to the structures. An incremental load is applied and then iteration is undertaken until a converged solution has been achieved. If failure is detected at a particular load level, then a material degradation model is needed in order to determine new estimates of the local material properties and the failure propagation. An implicit nonlinear analysis SOL 400, implemented in the MSC Nastran® solver, has been performed in order to evaluate the degradation at first-ply failure for the two models previously discussed. Load is applied by enforced displacement at the free end of the laminate, Fig. 16-17. Such sensitivity analysis has allowed for the emphasizing the inadequacy of an only linear approach to deepen the structural behavior especially in the case of innovative composite materials.

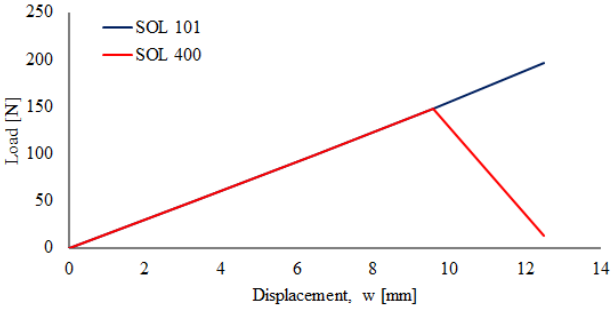

Fig. 16 First-ply failure prediction, Sample G

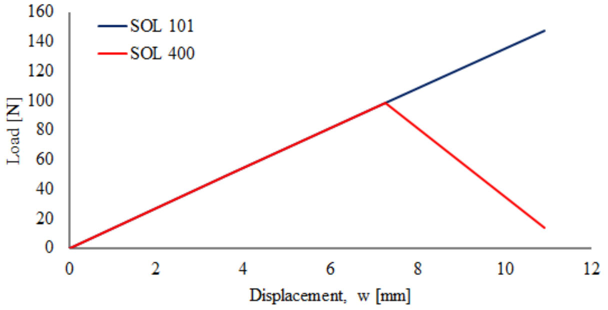

Fig. 17 First-ply failure prediction, Sample SH1

## IV. CONCLUSIONS AND FURTHER DEVELOPMENTS

For their peculiarities, such as the heterogeneity and anisotropy, composites are materials used as a solution to problems of different areas, taking advantage of lightweight, strength, stiffness, good behavior to fatigue, reduced manufacturing costs and weight reduction. Following the introduction of such materials in many industrial sectors, the study of the dynamics of the structures has become more significant over the years. The present work has conducted a research to examine preliminary the mechanical characteristics of an innovative laminate with a self-repair treatment. The self-healing design consists in dispersing microcapsules containing finely pulverized catalyst into the epoxy resin components. The solution is accurately mixed by mechanical agitation avoiding the formation of air bubbles [7]. The effectiveness of the proposed technological method has been assessed in terms of flexural static stiffness and damping capability compared to a standard CFRC specimen. Based on a well-correlated numerical model, 2D FEA of samples were carried out to predict the performance of the structures with respect to the first-ply failure according to the Tsai-Wu criterion implemented in the implicit nonlinear solver (SOL 400) [5]. The tests evidence has revealed an actually better behavior of the self-healing sample compared to the conventional one in terms of vibrational energy dissipation and global weight: the average damping coefficient, measured in two different ways has been found to be about four times higher with weight reduction of 36%. These very satisfactory outcomes encourage the experimentation and the application of these materials for the execution into a potential industrialization process. Further studies can be conducted on the original panels from which the coupons were extracted. It will be possible to investigate with greater accuracy by non-invasive measurement techniques like the laser vibrometry, the damping capacity of these materials in vibrational field as well as in terms of acoustic emission [1], [9]-[13].

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