DAMAGE MONITORING IN CFRP LAMINATES BY MEANS OF DIELECTRICAL PROPERTIES

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SUMMARY: Damage development in CFRP laminates subjected to quasi-static loading has been monitored by means of dielectrical measurements. Cross-ply and angle ply laminates have been subjected to bending stresses, while continuously recording the real (Z') and the complex (Z") components of the impedance. The results showed that both Z' and Z" were affected by transverse cracking during the early stages of the loading. These results were interpreted by considering that cracking is able to modify both the resistive and the capacitive components of the dielectrical response. Changes in Z' were related to the disruption of conducting paths between adjacent fibres, whereas changes in Z" were attributed to void formation in the cracked composite. By means of X-ray radiography, it was possible to establish a relationship between the progressive increase in crack density and the relative changes in Z' and Z".

KEYWORDS: CFRP Laminates, Damage Monitoring, Dielectric Properties, Intralaminar Cracking, Delamination.

INTRODUCTION

The development of non-destructive controls allowing damage detection in Carbon Fiber Reinforced Polymers (CFRP) during service life is a key problem in many practical applications, especially in the aircraft industry. Many of these non-destructive tests involve the periodic inspection of the composite parts by means of costly and specialized equipment's. There is thus a growing interest in the development of smart materials integrating sensors, which can allow in-situ damage monitoring during the whole service life of the structure.

In CFRP, carbon fibers can act as electric conductors (their resistivity ρ is in the order of $1{,}500.10^{-8}$ Ω.m) embedded in an insulating matrix ($\rho \approx 10^{20}$ Ω.m). Changes in the electrical properties can thus be expected to occur if some of the conducting paths within the composite are modified by virtue of damage development under mechanical loading. Over the past few years, this led to a growing interest in the potential of electrical measurements to detect the various kind of damage induced by mechanical loading in CFRP laminates. Encouraging results have been obtained by means of DC measurements in CFRP laminates subjected to quasi-static and fatigue loading [see e.g. 1-3]. It was especially demonstrated that the monitoring of electrical resistance allows the quantitative detection of damage in terms of fiber breaks, even at very low stress levels [4]. Depending on the stacking sequence, the DC measurements proved, however, not to be always suitable for the detection of transverse cracking and delamination. In such situations, some studies using carbon reinforced cements [5] or CFRP laminates [6] indicates that the measurement of the dielectrical response of materials can provide an alternative way of detecting such a damage. Voids associated to macroscopic cracking can especially induce changes in the capacitive component as well as in the resistive component of the dielectrical behaviour.

In this study, it was therefore attempted to use AC electrical measurements to detect cracking and delamination in CFRP laminates subjected to quasi-static loading. The potential of such measurements was investigated for both cross-ply and angle-ply laminate, where the initial damage consists mainly in transverse ply cracking and/or inter-ply delamination. In order to correlate the changes in the dielectrical response to the development of damage, AC measurements have been associated with crack detection by X-ray radiography.

RESULTS AND DISCUSSION

Materials and experimental techniques

Materials

The main material used in this study was a carbon fiber/epoxy laminate made of a CIBA 913 matrix reinforced by high resistance HTA7 fibers (Toho). The composite was processed by prepreg moulding in an autoclave (1^h30 at 125°C and 7 bars). Two stacking sequences were considered, namely $[+45;-45]_{8s}$ and $[90;0]_{8s}$. The fibre fraction was 49±4 vol%. Samples 100mm long, 10mm wide and 2mm thick were cut out for mechanical and electrical characterisation.

In addition, some tests were carried out using a $[90_3;0_3]_s$ laminate made of a CIBA 914 epoxy matrix reinforced by T300 (Toray) carbon fibers. This stacking sequence was selected for its suitability for transverse cracks detection by X-ray radiography. Specimens 100 x 10 x 1.5 mm^3 with a fibre volume fraction of *ca.* 58.6vol% have been used.

Post-buckling bending tests

A flexural loading has been selected in order to induce the highest density of cracks in the central part of the specimens where the electrodes were located. This loading configuration was found to allow a good detection of cracks by means of through-thickness dielectrical measurements. In order to avoid any perturbation of the electrodes by a loading nose, a post-buckling bending test was preferred to the classical three-point bending test. Composite specimens were clamped at each end in grips which can accommodate in plane rotation. A longitudinal compressive load greater than the Euler critical load was subsequently applied. The resulting specimen’s buckling induced a flexural moment. In order to ensure that the shear and compressive stresses are negligible, a length to depth ratio L/h>45 was selected [4]. The specimens were tested under quasi-static conditions at a loading rate equal to 1.2 $mm.min^{-1}$. The load P was recorded versus the longitudinal displacement δ and these values were used to compute the maximum stress and strain on the tensile side of the sample by means of a procedure described elsewhere [4].

Dielectrical measurements

AC measurements have been performed using a Solartron Instruments SI 1260 data acquisition system. The real (Z') and the imaginary part (Z") of the complex impedance were measured at 100 kHz and using a voltage amplitude equal to ±0.5 V. Dielectrical properties have been measured through the thickness of the specimen using two copper electrodes (10*3 mm^2) glued on two opposite sides in the central part of the specimens. Due to their low thickness (50 µm), these electrodes were able to sustain the applied flexural strain without any cracking or debonding from the specimen surface.

Quantitative detection of cracks by X-ray radiography

Matrix cracking and delamination were investigated by means of penetrant-enhanced X-ray radiography. Before exposure, a Zinc iodide solution was applied on each of the free surfaces of the coupons in order to allow diffusion into the cracks. Photographs of the specimens were subsequently produced by means of a Pantak industrial X-ray unit (exposure conditions : 13 kV, 38 mA, 2 min). Quantitative measurements of crack number have then been carried from the pictures.

Damage monitoring in the $[+45;-45]_{8s}$ laminates

Monotonic bending tests have been carried out using the $[+45;-45]_{8s}$ laminates, while continuously monitoring Z' and Z" (Fig. 1 and 2). The stress-strain relationship exhibited a quasi linear behaviour during the initial stages of the loading (ε<0.7%). In this domain, no significant changes in Z' and Z" were detected. When the strain was increased above 0.7%, the development of a non-linear mechanical response was associated with an increase in Z' and a decrease in Z". It can also be noted that the rate of the changes in the dielectrical parameters was enhanced as the strain was increased.

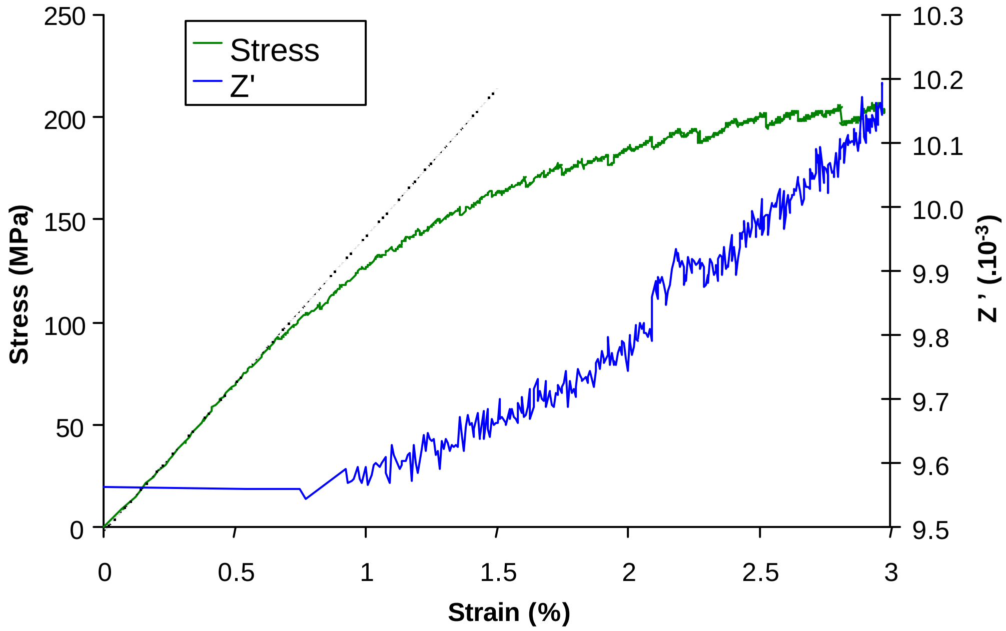

Fig. 1 : *Changes in stress and in Z' as a function of strain during a quasi-static loading ($[+45;-45]_{8s}$ laminate).*

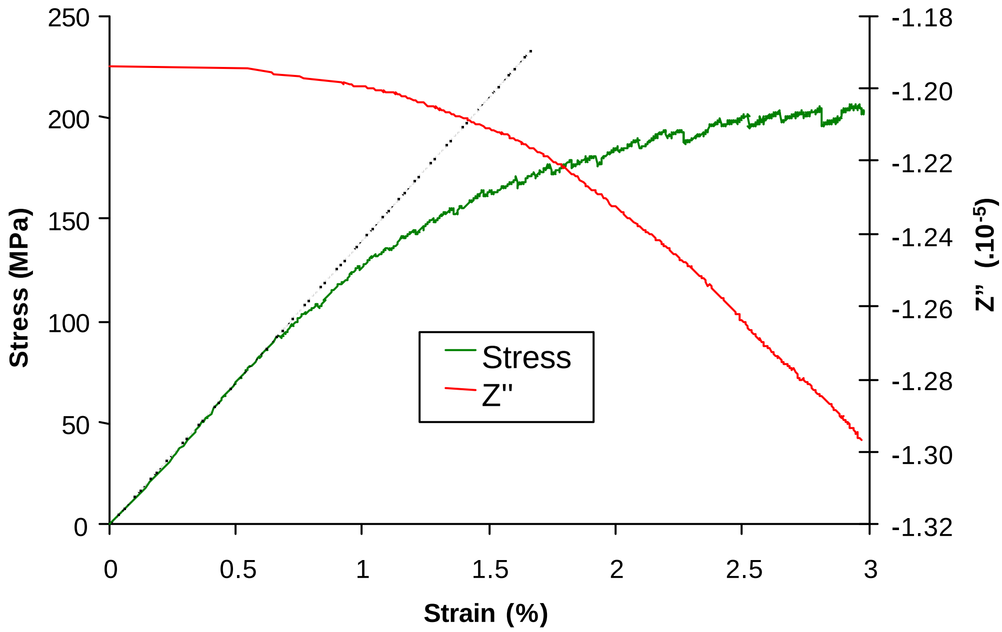

Fig. 2 : *Changes in stress and in Z” as a function of strain during a quasi-static loading ($[+45;-45]_{8s}$ laminate).*

The occurrence of changes in Z’ and Z” thus appear to be strongly correlated to the non linear behaviour observed on the stress-strain curve. It is widely established that the latter can be attributed to both visco-plastic deformation of the matrix and transverse cracking, although it is difficult to separate these two processes from the stress-strain curve. On the other hand, the dielectrical properties can be assumed to be only sensitive to the development of cracks and to remain unaffected by the visco-plastic flow of the matrix. Cracking may result into two effects regarding the AC response of the composite:

(i) an increase in the resistive component of the material due to the breakage of conducting paths between contacting fibres. The fibre fraction of the studied composite is effectively above the percolation threshold values (about 40vol%) reported in the literature for continuous carbon fibre reinforcement in polymer matrix [7,8]. As a result, some electrical conduction can occur along the transverse direction by fibre to fibre contacts. This was experimentally confirmed by through thickness DC measurements which provided a resistance of *ca*. 2.1 Ω. When macroscopic cracks propagate within or between the plies, some fibre to fibre contacts are disrupted and this may result in an increase in Z’.

(ii) the macroscopic damage can also induce a change in the capacitive response of the composite. Crack opening lead to the formation of cavities filled with air or vacuum. If it is kept in mind that the capacitance is proportional to the material permittivity and that the permittivity of an epoxy matrix is about seven times these of air, it becomes clear that cracks will enhance capacitive effects in the composite.

If some assumption are made regarding the dielectrical behaviour of the composite, relationships can be established between the components Z’ and Z” of the complex impedance and the resistance R and the capacity C of the material. As a first approximation, the material can be supposed to behave as a parallel RC circuit. In such conditions, the following equations can be derived:

$$Z' = \frac{R}{1 + R^2 C^2 w^2} \tag{1}$$

where ω is the pulsation of the voltage signal.

$$Z'' = \frac{-R^2 C w}{1 + R^2 C^2 w^2} \tag{2}$$

In a similar way, R and C can be related to Z' and Z" as follows :

$$R = \frac{Z'^2 + Z''^2}{Z'} \tag{3}$$

$$C = \frac{-Z''}{(Z'^2 + Z''^2) w} \tag{4}$$

with

$$C = e_0 e_r \frac{S}{e} \tag{5}$$

where ε_0 is the vacuum permittivity and ε_r the relative permittivity of the material.

According to these equations, changes in R and C associated to cracking will affect both Z' and Z". It must, however, be emphasised that transverse cracks and interply delamination do not necessarily affect Z' to the same extent. Intra-ply cracks are oriented perpendicular to the electrodes, i.e. in a direction parallel to the main conducting paths. As a result, they can be supposed to have a minor effect on the resistive component. On the other hand, interply delamination can induce a more significant increase in the resistive response, because these defects are oriented perpendicular to the conducting paths. Similar orientation effects are not expected regarding the capacitive component, which is supposed to depend only on the volume of the voids created by either delamination or transverse cracking.

Following these assumptions, Z' should be more sensitive to delamination than to transverse cracking. The two following situations may thus schematically be envisaged:

-a simultaneous change in Z' and Z", which would indicate the occurrence of delamination in addition to transverse cracking.
-on the opposite, an increase in Z" while Z' remains constant could be interpreted as an evidence of the development of transverse cracks without delamination.

SEM observation (Fig. 3) of the specimens after testing support these conclusions. Both inter-ply delamination and transverse cracking were observed, which is consistent with the occurrence of changes in Z' and Z" during loading.

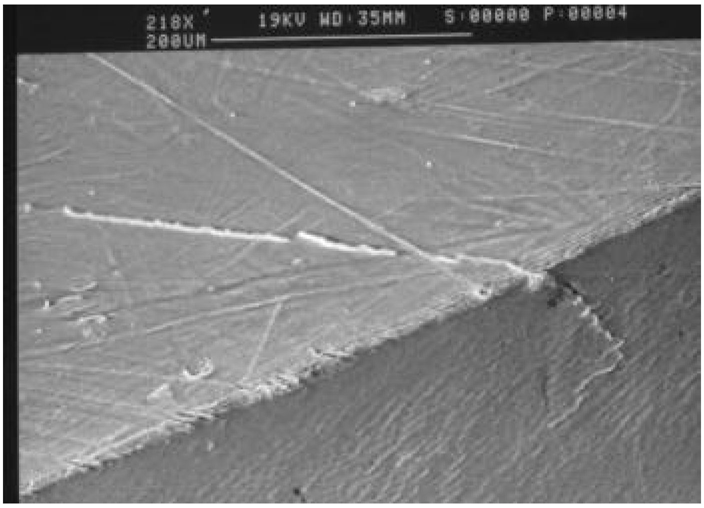

Fig. 3: *SEM observation of the tensile face of a specimen showing evidence of transverse cracks and delamination ([+45;-45]$_{8s}$ laminate, ε=3.0%).*

Damage monitoring in [90;0]$_{8s}$ laminates

Similar quasi-static test were performed using [90;0]$_{8s}$ laminates with the external plies oriented to 90 degrees to the applied load. In that configuration, the changes in Z' and Z" involved three different steps (Fig.4):

(i) for $\varepsilon<1\%$, no significant perturbation of the dielectrical response was observed,
(ii) for $1\%<\varepsilon<1.7\%$, Z" decreased while Z' remained constant,
(iii) above 1.7% strain , a simultaneous increase in Z' and decrease in Z" was measured. In this strain range, the stress-strain curve was characterised by the development of a non linear behaviour up to failure.

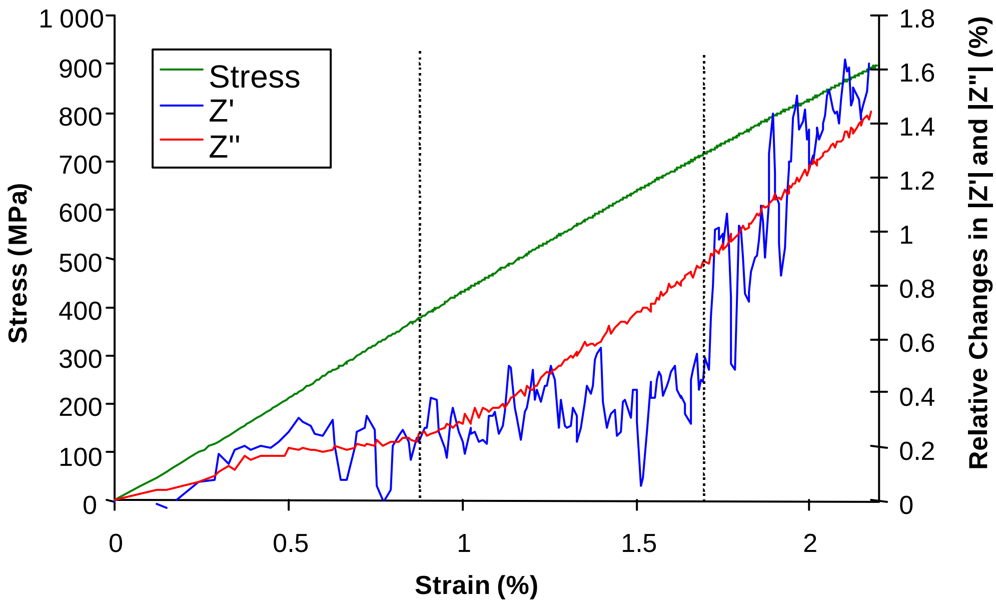

Fig.4: Relative changes in Z' and Z" vs the applied strain ([90;0]$_{8s}$ laminate).

SEM observations (Fig.5) showed that, up to 1.7%, the damage was only related to transverse cracks in the upper 90 degree ply, without any evidence of inter-laminar cracks. The observed transverse cracks induced the formation of voids which can account for the increase in the capacitive component Z”. The fact that Z’ did not change in that strain range tends to demonstrate that the conducting paths along the transverse direction were not significantly affected by cracking.
For ε>1.7%, the increase in Z’ can be attributed to an increased density of cracks or to the appearance of interply delamination close to the failure strain of the composite. In order to establish a more quantitative relationship between the dielectrical response and the density of cracks, an attempt was made to investigate the kinetics of damage development by X-ray radiography. These technique proved, however, not to be sensitive enough to detect the very thin cracks which were induced in the upper ply. To overcome this problem, we have selected a $[90_3;0_3]_s$ laminate with the three outer plies oriented perpendicular to the applied load. In this material, the size of the cracks induced in the 90° layer was found to be consistent with the resolution of the X-ray technique.

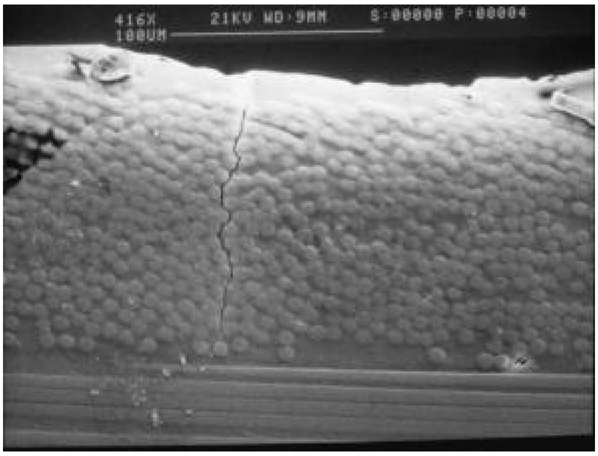

Fig. 5: *SEM observation of the tensile face of a specimen showing evidence of transverse cracks ($[90;0]_{8s}$ laminate, ε=1.7%).*

Relation between crack density and dielectrical properties

During the flexural loading, the initial damage was related to transverse cracks in the outer plies of the $[90_3;0_3]_s$ laminates. The kinetics of damage development was monitored by flexural tests carried out at increasing strain levels. At the end of each test, the number and the location of the transverse cracks in the specimen was determined. In Fig.6, results are reported as a function of strain level. For the comparison with dielectrical measurements, only the fraction of electrically active cracks located between the electrodes must be considered. Above a strain threshold close to 0.7%, it was observed that density of of cracks increased progressively until a saturation level close to 2%. No further transverse cracking was detected until the final failure of the 0 degree plies.
Very similar trends were observed regarding the changes in Z’ and Z” (Fig. 7). Above 1% strain, a continuous change in the dielectrical parameters occurred up to specimen failure. Moreover, it can be noted that the rate of these changes decreased above a strain about 2%, i.e. in the range where a saturation in transverse cracking was observed by X-Ray radiography. At this stage, it can be assumed that the changes in Z’ and Z” were mainly due to the opening of the existing cracks and to some delamination.

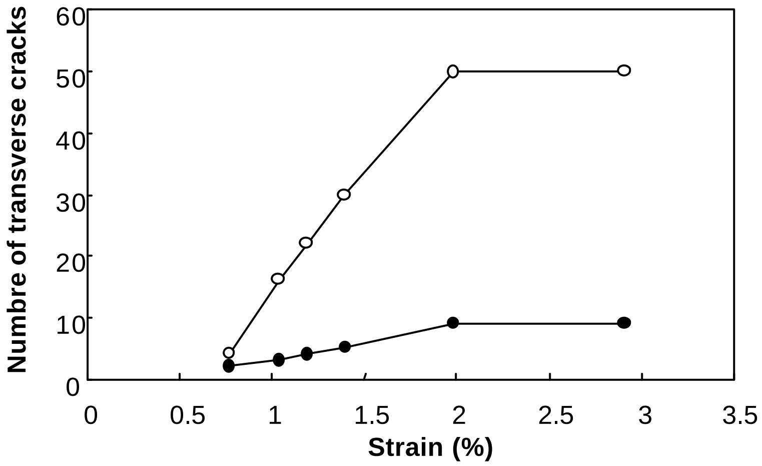

Fig. 6: Number of transverse cracks vs. maximum applied strain for $[90_3;0_3]_s$ laminates. (①) total number of cracks; (⑨) cracks located between the electrodes

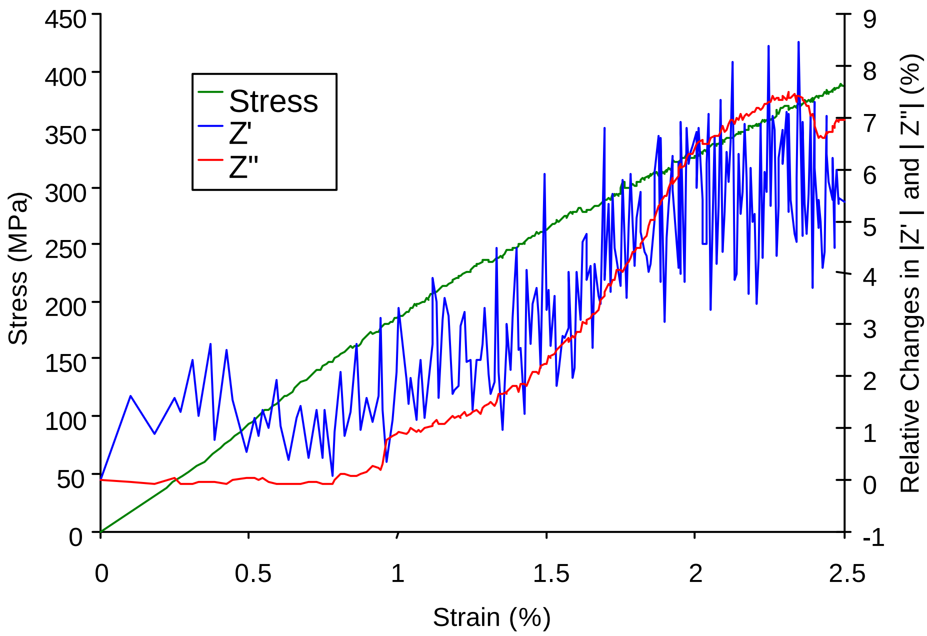

Fig 7: Relative changes in Z' and Z" vs the applied strain ($[90_3;0_3]_s$ laminate).

Contrary to the $[90;0]_{8s}$ laminate, Z' varied simultaneously to Z" during the early stages of the development of transverse cracking. This can be attributed to the fact that the size and the opening of the cracks was much more important in this laminate, due to the increased thickness of the 90 degree layer. As a result, the disruption of the conducting paths associated to transverse cracking was probably significant enough to induce a change in the resistive component during the early stages of damage development.

CONCLUSIONS

The potential of dielectrical measurements to monitor damage development in CFRP laminates has been assessed. The results demonstrated that both Z' and Z" were affected by transverse cracking and delamination, which occurred during quasi-static flexural loading. Moreover, a comparative analysis between dielectrical properties and crack density revealed that AC measurements provide a sensitive mean of detecting the first damage occurring in CFRP laminates. If the material is assumed to behave like a parallel RC circuit, difference in the relative changes in Z' and Z" may also give some information regarding the nature of the damage and the orientation of the defects. It is however clear that a more quantitative analysis of the damage from AC measurements would require a better theoretical description of the dielectrical behaviour of CFRP laminates.

ACKNOWLEDGEMENTS

The authors fully acknowledge *Hexcel Composites* (Dagneux, France) and the *Direction des Recherches et Etudes Techniques* (DRET, France) for their financial and technical support.

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