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Tensile and fatigue testing of impacted smart CFRP composites with embedded PZT transducers for nonlinear ultrasonic monitoring of damage evolution

Christos Andreades¹, Michele Meo¹  and Francesco Ciampa² 

¹ Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY, United Kingdom

² Department of Mechanical Engineering Sciences, University of Surrey, Guildford, GU2 7XH, United Kingdom

E-mail: f.ciampa@surrey.ac.uk

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Abstract

Ultrasonic systems based on ‘smart’ composite structures with embedded sensor networks can reduce both inspection time and costs of aircraft components during maintenance or in-service. This paper assessed the tensile strength and fatigue endurance of carbon fibre reinforced plastic (CFRP) laminates with embedded piezoelectric (PZT) transducers, which were covered with glass fibre patches for electrical insulation. This sensor layout was proposed and tested by the authors in recent studies, proving its suitability for nonlinear ultrasonic detection of material damage without compromising the compressive, flexural or interlaminar shear strength of the ‘smart’ CFRP composite. In this work, CFRP samples including PZTs (G-specimens) were tested against plain samples (P-specimens), and their mean values of tensile strength and fatigue cycles to failure were found to be statistically the same (910 MPa and 713 000 cycles) using the one-way analysis of variance method. The same tests on P- and G-specimens with barely visible impact damage (BVID) showed that the corresponding group means were also the same (865 MPa and 675 000 cycles). Nonlinear ultrasonic experiments on impacted G-samples demonstrated that embedded PZTs could monitor the growth of BVID during fatigue testing, for a minimum of 480 000 cycles. This was achieved by calculating an increase of nearly two orders of magnitude in the ratio of second-to-fundamental harmonic amplitude. Finally, PZT transducers were confirmed functional under cyclic loading up to ~70% of sample’s life, since their capacitance remained constant during ultrasonic testing.

Keywords: composite materials, smart structures, fatigue test, nonlinear ultrasound

(Some figures may appear in colour only in the online journal)

1. Introduction

A large percentage (~50%) of metal components that were traditionally used in aerospace structures has been replaced

with fibre reinforced plastic (FRP) composite materials [1, 2]. The reason is the high strength and stiffness, low weight, corrosion resistance and fatigue performance that FRP materials exhibit, enabling the development of structures with advanced durability and safety [3]. Carbon fibre reinforced plastic (CFRP) is the most commonly used composite material as it offers the best balance of the above properties. However, the biggest drawback of CFRP parts is that, unlike metallic components, they can sustain internal damage due to



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impact events with nearly invisible marks on their surface, known as barely visible impact damage (BVID) [4]. Normally, BVID from bird strikes, hailstorms and tool drops is characterised by delamination, matrix micro-cracking and fibre failure [5]. These material flaws tend to evolve with high rates under operating dynamic stresses and, thus, safety regulations in aviation require frequent inspections of composite structures [6]. These inspections can result in time delays and high costs, especially when the aircrafts must be set out of service for visual examination or scanning using various non-destructive evaluation (NDE) techniques. Examples of NDE inspection include methods relying on ultrasonic wave propagation [7, 8], acoustic emission [9, 10], electromagnetic radiation [11, 12], thermal imaging [13, 14] and shearography [15, 16]. Although NDE methods are effective in detecting material damage, they are not ideal for in-service inspection due to size and weight limitations [17]. As an alternative, the fabrication of ‘smart’ composites with incorporated networks of piezoelectric lead zirconate titanate (PZT) sensors has gained considerable attention because it enables the conversion of ultrasonic NDE techniques into structural health monitoring (SHM) systems for in-flight inspection of aerospace structures [18]. Ultrasonic methods relying on the examination of the nonlinear features exhibited in the material response have been proved more sensitive and effective in the detection of micro-cracks than linear ultrasonic techniques [19–22]. Nonlinear effects such as (a) higher harmonic and sub-harmonic generation [23–28], (b) wave modulation [29–33] and (c) nonlinear resonance [34–37] can be generated in the material spectrum due to clapping and/or frictional movement of the crack surfaces caused by their interaction with propagating waves. Among these phenomena, higher harmonic generation and, particularly, second harmonic generation, is widely considered an indication of damage existence. With this method, the level of material nonlinearity can be quantified based on the second-order elastic coefficient known as the parameter β , which is proportional to the ratio of second-to-fundamental harmonic amplitude [38]. The value of β has already been found to increase with growing damage size [39–41].

In regard to the fabrication of ‘smart’ CFRP composites for ultrasonic SMH monitoring, many studies focused on the use of internally rather than externally-bonded PZT transducers, in order to eliminate the need for expensive and heavy sensor shielding, and to minimise sensor wear from exposure to harsh environmental conditions [42–46]. On the other hand, PZTs inside CFRP composites must have insulated electrodes to prevent direct contact with carbon fibres. The usual practice in literature involves separation of the sensor from the composite plies using polymeric layers such as Kapton film, but this can lead to inappropriate ply adhesion and eventually delamination with serious effects on the structural integrity of the material [19, 47, 48].

In a previous study from the authors [49], a novel material processing method was proposed for the electrical insulation of PZT disks that were directly inserted between the layers of CFRP plates. This method relied on covering the top conductive side of the PZTs with single-layer patches of

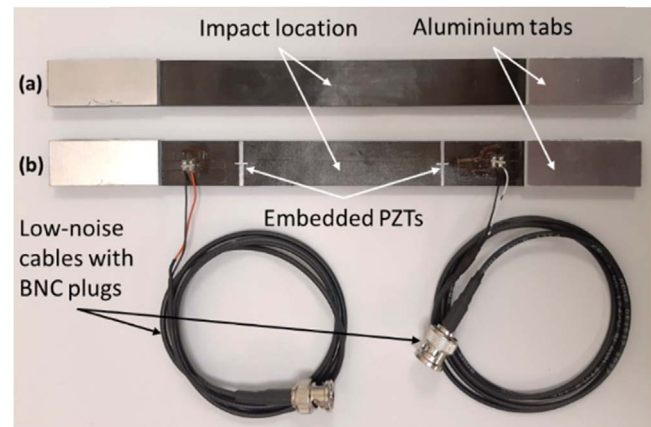


Figure 1 Illustration of P-specimen (a) and G-specimen (b) used in this study.

dry E-glass fibre fabric to avoid contact with carbon fibres. The ‘smart’ CFRP composite was subject to monotonic (static) mechanical testing including short-beam and long-beam three-point bending tests, and compression tests. The mean values of interlaminar shear, flexural and compressive strength were found to be equal to the means of plain CFRP composites. Although these results were promising, one of the main requirements for ‘smart’ SHM composites is their durability under dynamic loading conditions, which can progressively damage the sensors and their interconnections. Available studies on CFRP composites with internal PZTs examined the functionality of sensors during fatigue testing by recording the change in output voltage or signal amplitude [50–53]. However, the monitoring of damage evolution with increasing number of fatigue cycles was not accomplished, and this is one of the main areas of interest of this paper.

In particular, this study focused on the assessment of (i) the mechanical performance of the ‘smart’ CFRP composite under cyclic loading, and (ii) the capability of the embedded PZTs to monitor the increase in damage size with repeated loading based on nonlinear ultrasonic testing. To achieve these two objectives, impact damaged CFRP samples containing pairs of glass fibre insulated PZTs (G-specimens) were subject to tension–tension fatigue testing, and their endurance was compared with that of plain samples (P-specimens). The design of the test samples is shown in figure 1. Static tensile testing was also required as part of fatigue testing procedure, for the determination of the material strength. That was an opportunity to study the tensile strength of the G-specimens against that of P-specimens. In relation to the nonlinear ultrasonic experiments, the PZTs inside the G-specimens were used for the propagation of elastic waves through the material, and the calculation of the nonlinear parameter β at different stages of fatigue testing.

2. Second-order acoustic nonlinearity parameter

Tight cracks with contact surfaces inside composite plates can interact with propagating ultrasonic waves. The compressive

part of the waves tends to close the crack interface whereas the tensile part to open it. Hence, cracks behave as half-wave rectifiers allowing only the compressive part of the wave field to propagate through. This means that the material stiffness at the damage location is higher in compression and lower in tension, and this asymmetry changes the local stress-strain relationship into nonlinear [54]. The contact ('clapping') between the crack surfaces can generate new waves of twice the frequency of the incident waves, which are detectable in the form of even higher harmonics. Conversely, the friction between the crack surfaces due to slipping ('rubbing') motion changes the local stiffness symmetrically, leading to the generation of odd higher harmonics [54]. Nevertheless, in literature, the detection of second-order frequency harmonics has been broadly associated with the presence of defects [55, 56], as it allows direct calculation of the material non-linearity. Briefly, the equation describing the propagation of one-dimensional elastic waves in the x -direction of the material has a second order approximation of

$$\frac{\partial^2 u(x, t)}{\partial t^2} - c^2 \frac{\partial^2 u(x, t)}{\partial x^2} = \beta c^2 \left(\frac{\partial u(x, t)}{\partial x} \right) \left(\frac{\partial^2 u(x, t)}{\partial x^2} \right), \quad (1)$$

where $u(x, t)$ and c are the displacement and speed of waves respectively, and parameter β is an elastic coefficient describing the second-order material nonlinearities. By solving equation (1) using a first-order perturbation method, β can be expressed as [57]:

$$\beta = \frac{8A_2}{A_1^2 x k^2}. \quad (2)$$

In equation (2), A_1 and A_2 are equal to the wave amplitude at the fundamental and second harmonic frequencies, x is the wave propagation distance inside the material and k is the wave number. Considering that x and k are constants, the nonlinear parameter β becomes proportional to the following ratio [57]:

$$\beta \propto \frac{A_2}{A_1^2}. \quad (3)$$

The ratio described in equation (3) can be used as an indicative measure of the second order nonlinearity arising from the second harmonic behaviour of other types of waves (e.g. guided waves) exhibited in the medium from the interaction of the input waves with defects or material edges. In general, as material damage grows with repeated loading, a drop in A_1 amplitude and a rise in A_2 amplitude is expected due to acoustic energy transfer from A_1 to A_2 . Therefore, for impact damaged composite plates subject to fatigue testing, the value of β is expected to increase with increasing number of cycles. In fact, it has already been shown experimentally that there is a strong correlation between fatigue damage and β , because second harmonic has the highest elastic energy content among other nonlinear harmonic frequencies (third, fourth, etc) [58–62].

3. Experimentation

3.1. Fabrication of test samples

Likewise previous studies from the authors [49, 63], the composite specimens were manufactured using twelve uni-directional prepreg layers (Hexcel T800/M21) that they were laid by hand in $[0^\circ/90^\circ/0^\circ/90^\circ/0^\circ/90^\circ]$ s orientation. The in-plane size of samples was 260×20 mm with a nominal thickness of 3 mm. Aluminium end-tabs ($50 \times 20 \times 1.5$ mm) were bonded to these samples using a two-part epoxy adhesive (Araldite 420 A/B), as shown in figure 2. The specimens were divided into two groups. The first group was that of plain CFRP samples, here called P-specimens. The second one included CFRP samples with pairs of embedded PIC 255 piezoelectric disks (6 mm diameter $\times$ 0.3 mm thick) each of which was covered with a dry fabric layer of E-glass fibres (10×10 mm $\times$ 0.1 mm) for electrical insulation. These samples are referred as the G-specimens in this paper. The PZTs with the glass fibre layers were symmetrically placed 85 mm away from the specimen ends (figure 2), at the interface between the 4th and the 5th plies (above the middle plane). Each of the four CFRP plies above the sensor interface included short and narrow openings in the fibre direction (i.e. no fibre cutting) through which the positive and negative wires of the PZTs were directed outside the top surface of the plates. The wire ends were attached to low-noise cables (RG174/U) with BNC plugs (50 Ω).

3.2. Impact damaging of test samples

Composite specimens were initially impacted at their centre using a testing machine configuring a 2.66 kg drop mass with a hemispherical tip of 20 mm diameter. Multiple impacts of different energy were performed on spare samples for the determination of the energy level required to cause BVID to the material.

The energy was controlled by adjusting the drop height accordingly, and the material damage was examined through stepped linear C-scanning using an ultrasonic imaging system (from Diagnostic Sonar Ltd) equipped with a phased array transducer (5 MHz, 128 elements). As can be seen in figure 3, an impact energy of 3 J was high enough to introduce delamination and matrix cracking into the CFRP samples without any visible breakage of fibres. Hence, for consistency, all of the test samples with BVID used in the tensile and fatigue tests of this work were impacted with 3 J using the same testing facility and clamping layout.

3.3. Tensile and fatigue tests

Prior to performing fatigue tests, the ultimate tensile strength (UTS) of the P-specimens was calculated and compared with that of the G-specimens. In accordance with ASTM D 3039/D 3039M standard [64], five undamaged samples of each group were tensile loaded on a 100 kN servo-hydraulic Instron 1342 testing frame, at a displacement rate of 1 mm min^{-1} . Since all samples failed at a very similar maximum load of around 60 kN, the UTS of P- and G-samples

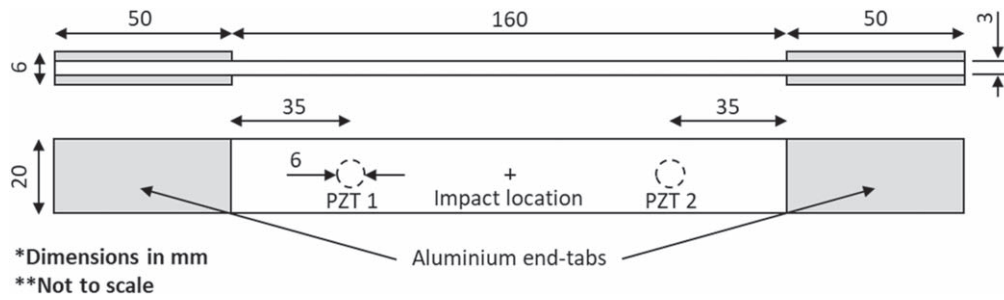


Figure 2. Design of test specimens.

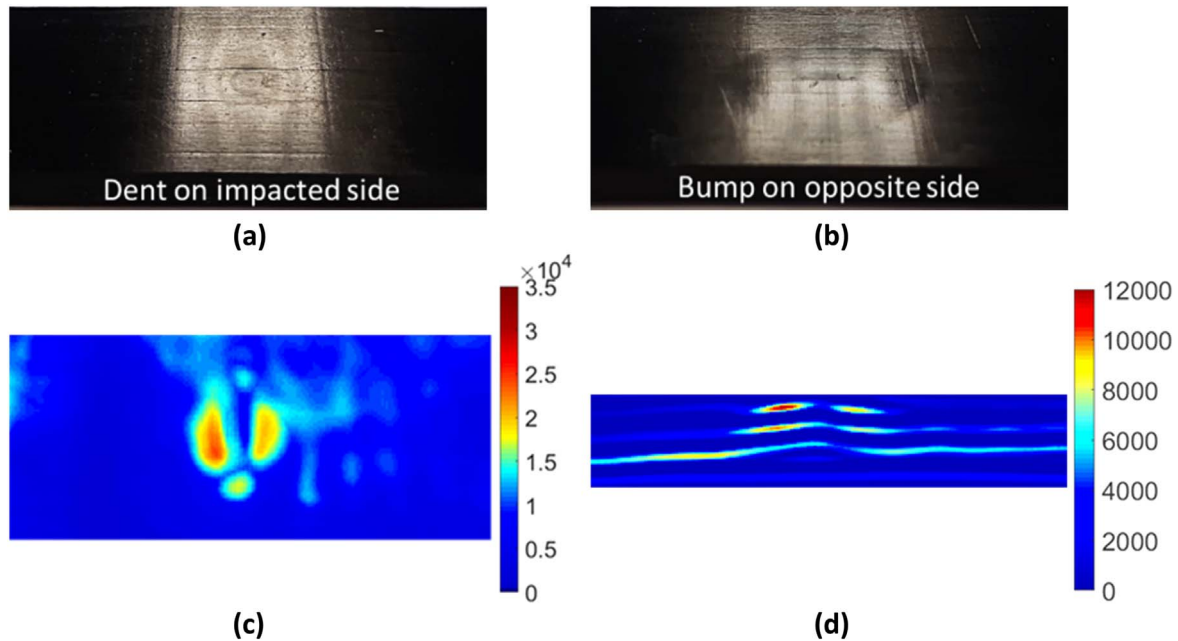


Figure 3. BVID on top (b) and bottom (c) specimen surfaces from 3 J impact, and the associated C-scan (c) and B-scan (d).

with BVID was then determined by tensile testing three samples of each type.

After completing the tensile tests, five P- and five G-specimens with BVID were used to perform tension-tension fatigue tests based on the ASTM D3479/D 3479M standard [65], using the same 100kN servo-hydraulic testing machine. In these tests, the samples were subject to sinusoidal waveform loading of constant amplitude (4.5–45 kN) with a cyclic frequency of 5 Hz. The lower and upper load limits corresponded to the 7.5% and 75% of the maximum tensile load of undamaged samples (~60 kN) as mentioned in the previous paragraph. Finally, three P-samples and three G-samples without damage were also fatigue tested within the same stress limits, to compare their endurance when starting from the pristine condition.

3.4. Functionality of embedded transducers

It is important to note that damaging of the embedded PZTs (e.g. cracking) due to cycling loading, or sensor depoling due to curing conditions (e.g. high pressure and temperature) would affect the performance of transducers during the ultrasonic tests for damage monitoring. In such case, part of

the change in parameter β would be related to sensor malfunction. Therefore, the capacitance of the PZTs inside the G-specimens was measured using a digital multimeter (Keithley 2110 5 1/2) before starting the fatigue tests, and after completing each interval of 120 thousand cycles. This is a common practice in literature for confirming the functionality of PZTs before using them for data acquisition [53, 66, 67]. In fact, any noticeable decrease in capacitance would indicate possible sensor damaging.

3.5. Nonlinear ultrasonic monitoring of damage evolution

Nonlinear ultrasonic tests were conducted on three impact-damaged G-specimens subject to fatigue testing. The aim was to demonstrate that the growth of BVID with increasing number of loading cycles could be monitored using the embedded PZTs. This was achieved by removing all three G-specimens from the Instron testing machine every 120 thousand cycles, and by recording their acoustic response using the set-up presented in figure 4. In particular, the transmitter PZT was excited with a continuous sinusoidal signal of constant amplitude (100 V) using a waveform generator (TTi TGA12104) in series with an amplifier (Falco

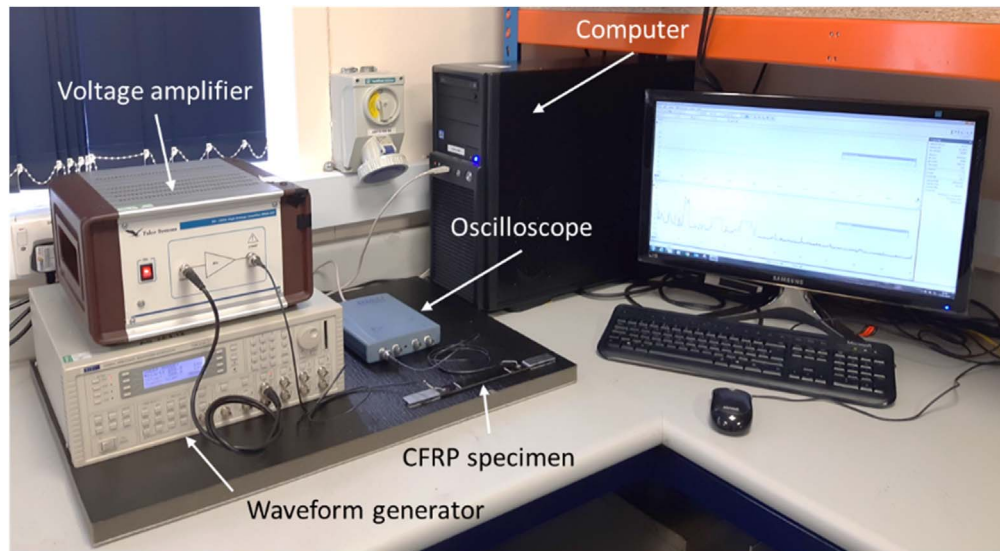


Figure 4. Illustration of the set-up used in the nonlinear ultrasonic experiments.

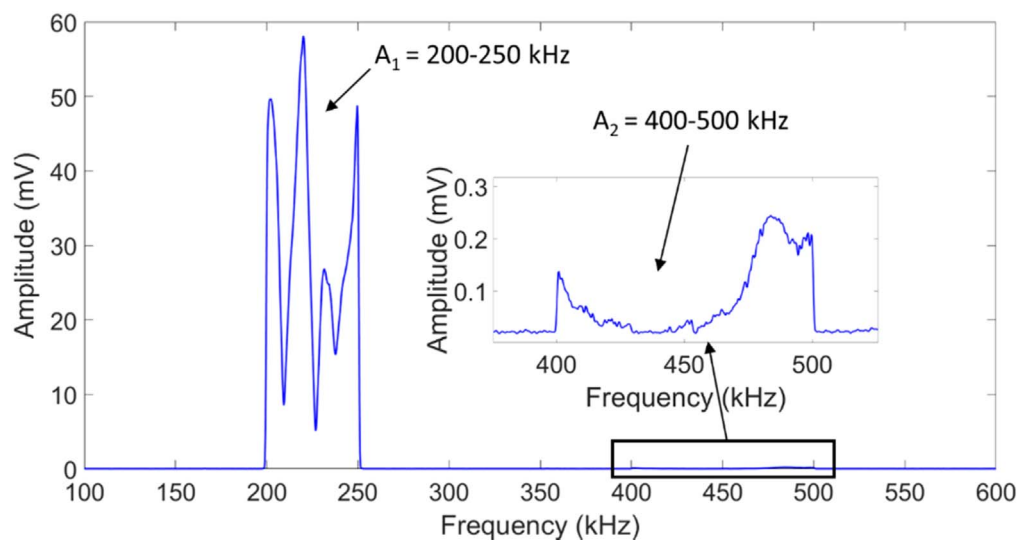


Figure 5. Received signal amplitude in frequency spectrum of G-specimen after 120 k fatigue cycles—case of 100 V input signal between 200–250 kHz.

Systems WMA-300). The second PZT was connected to an oscilloscope (PicoScope 4424) for acquisition of the propagating waves at a sampling rate of 10 MHz and a time window of 2 ms. At first, the frequency of the driving waveform was swept in the range of 80–600 kHz in steps of 20–50 kHz. Then, for every input frequency, the amplitude of A_1 and A_2 harmonics was obtained from the average frequency spectrum of the received signal, without using any band-pass filters. This allowed the calculation of the nonlinear parameter $\beta (\propto A_2/A_1^2)$ across the range of 80–600 kHz, during fatigue testing. An example of the acoustic response of one G-specimen after completing the first 120 000 loading cycles is illustrated in figure 5.

4. Results and discussion

4.1. Tensile and fatigue testing results

In tensile tests, the P- and G-specimens (both intact and impacted) failed by lateral through-thickness shear at the centre of their un-tabbed length (impact location), as shown in figures 6 and 7. Considering that the tabbed sections of the samples were free of damage, this type of failure was acceptable according to the ASTM D 3039/D 3039M standard. This indicated that in each case of initial sample state (undamaged or impacted), the failure behaviour under static tensile loading was the same between the P-specimens the G-specimens, using the proposed layout of embedded sensors.

The composite samples used in tension-tension fatigue tests experienced explosive failure at the impact location



Figure 6. Tensile failure of specimens without BVID. Top view (a) and side view (b) of P-specimen, and top view (c) and side view (d) of G-specimen.

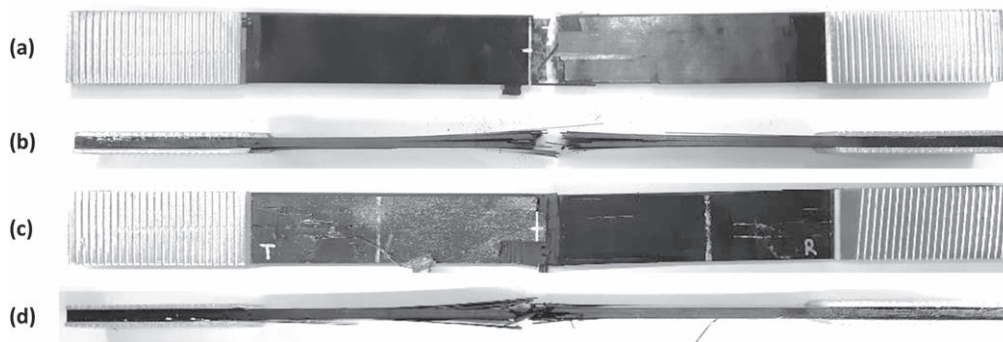


Figure 7. Tensile failure of specimens with BVID. Top view (a) and side view (b) of P-specimen, and top view (c) and side view (d) of G-specimen.



Figure 8. Tension–tension fatigue failure of specimens without BVID. Top view (a) and side view (b) of P-specimen, and top view (c) and side view (d) of G-specimen.

without any damage in the end-tabs of the specimen. With reference to the ASTM D3479/D 3479M standard, this failure mode was valid. As it is shown in figures 8 and 9, there was not any noticeable difference between the two specimen groups (P- and G-specimens). This proved that the evolution of material damage in the G-samples was not affected by the presence of the internal transducers, and it was true for both cases of initial sample condition: pristine and impacted.

The results from the tensile and fatigue tests were subject to a standard one-way analysis of variance (ANOVA) method using Matlab. This technique enabled to determine

statistically whether the mean values of the specimen groups were significantly different between the undamaged P- and G-samples and between the impacted P- and G-samples. In addition, ANOVA was chosen for consistency purposes, as it has already been used in a previous study of the authors to analyse the results from compressive, flexural and inter-laminar shear tests on the same ‘smart’ composite samples [49]. In this analysis, the null hypothesis (H_0) was that the group means were the same whereas the alternative hypothesis (H_A) was that the means were different, with a significance level (α) of 0.1 (i.e. 90% confidence level). In

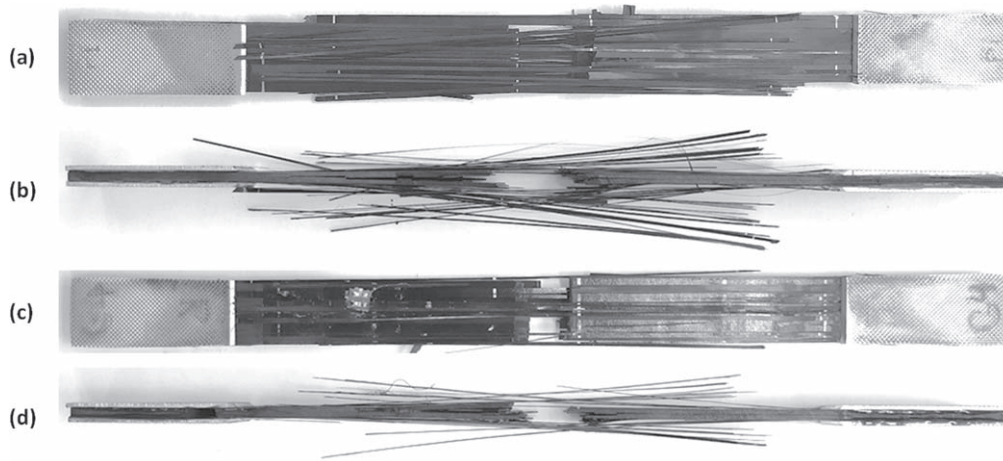


Figure 9. Tension-tension fatigue failure of specimens with BVID. Top view (a) and side view (b) of P-specimen, and top view (c) and side view (d) of G-specimen.

Table 1. Summary of tensile and fatigue testing results.

Test	Property	Pristine P-specimens	Pristine G-specimens	Impacted P-specimens	Impacted G-specimens
Tensile	Ult. Strength (MPa) ^a	916.8 (36.2)	903.4 (31.1)	871.2 (34.4)	859.5 (38.9)
	<i>F</i> -value	0.35	0.86		
	<i>p</i> -value	0.57	0.41		
	Max. Extension (mm) ^a	1.82 (0.11)	1.79 (0.15)	1.73 (0.14)	1.71 (0.10)
	<i>F</i> -value	0.05	0.16		
	<i>p</i> -value	0.83	0.70		
Fatigue	Cycles to failure ($\times 10^3$) ^a	720 (30.4)	705 (25.4)	683 (58)	667 (46)
	<i>F</i> -value	0.43	0.23		
	<i>p</i> -value	0.55	0.64		

^a Standard deviation in brackets.

general, the *F*-value (or *F*-statistic) in one-way ANOVA describes the following ratio

$$F = \frac{\text{Between} - \text{group variance}}{\text{Within} - \text{group variance}},$$

which is expected to be equal or close to 1 if H_0 is valid. Also, *F*-value is characterised by an *F* distribution with *k*-1 numerator degrees of freedom and *n*-*k* denominator degrees of freedom, where *k* is the number of groups and *n* is the total number of values from all *k* groups. From the cumulative distribution function of the *F* distribution, ANOVA calculates the probability (*p*-value) that the *F*-value can exceed the computed test-statistic. The null hypothesis is rejected for *p*-values less than α ($p < 0.1$) indicating that the group means are significantly different. Inversely, for $p > 0.1$ the null hypothesis is accepted. Based on the above, the mechanical testing results along with the *F*- and *p*-values are summarised in table 1.

Starting from the tensile tests, the pristine P- and G-specimens failed on average at a maximum stress of 910 MPa and a maximum extension of 1.81 mm. The ANOVA confirmed that the two specimen groups had the same means of ultimate tensile strength ($p = 0.57$) and maximum extension ($p = 0.83$). In the case of impact-damaged P- and G-samples, failure occurred at an average

stress of 865 MPa and an average extension of 1.72 mm. Again, the ANOVA outcome suggested that the samples with and without PZTs had equal values of tensile strength and extension, i.e. $p = 0.41$ and $p = 0.70$, respectively. It must be mentioned that the extension results referred to the total extension of the system and not the elongation of the sample, because the Instron readings included the stretching of the machine grips and the aluminium end-tabs. Nevertheless, the extension results were reported as an additional parameter for comparison, and they certainly showed high consistency between the two specimen groups.

About the tension-tension fatigue tests, the number of cycles to failure for the P- and G-specimens without impact damage was about 713 000, and the group means were considered the same based on the *p*-value of 0.55. Similarly, the maximum number of loading cycles for the impacted P- and G-samples was nearly 675 000, without any significant difference between the group means ($p = 0.64$). The results from these mechanical tests revealed that the presented configuration of embedded PZTs had no effect on the strength or the endurance of the 'smart' CFRP composite when subject to static or dynamic tensile loading conditions.

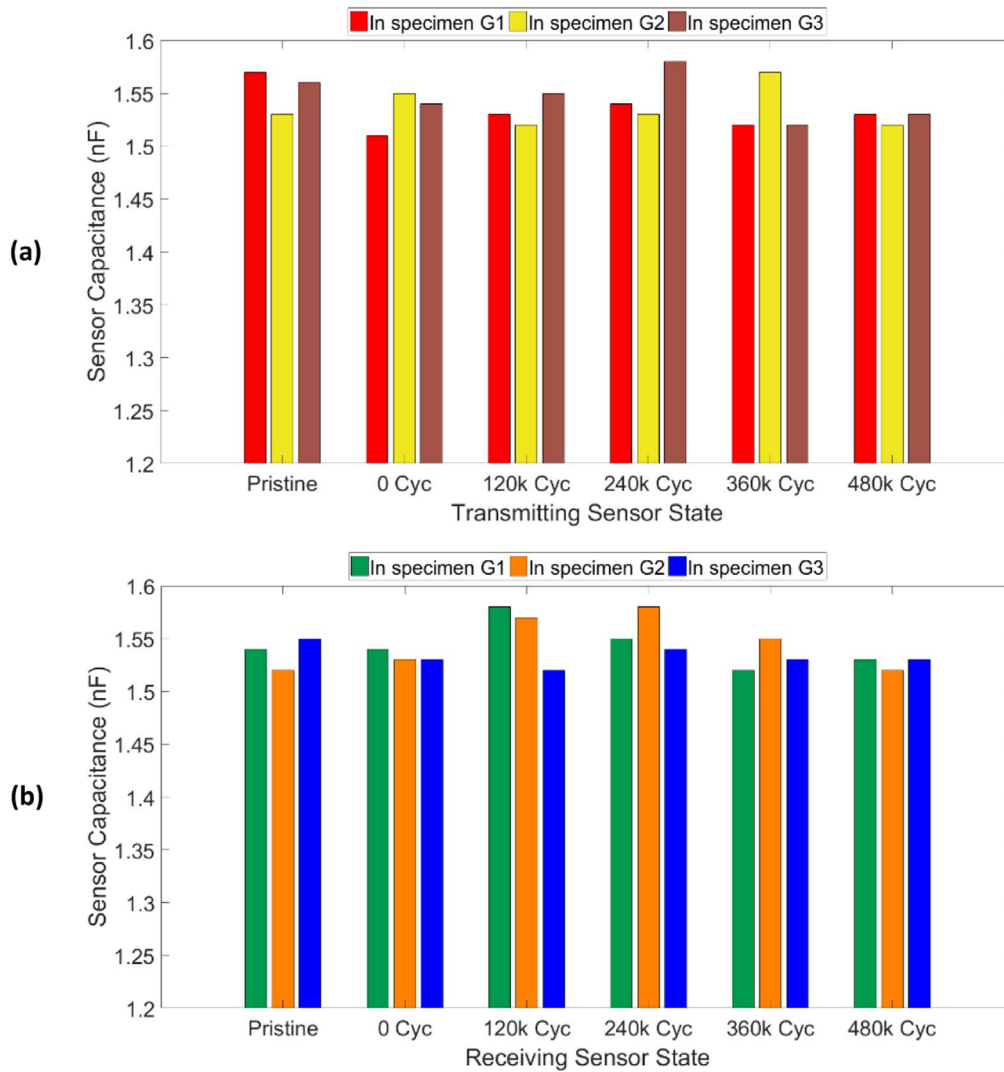


Figure 10. Capacitance of transmitting (a) and receiving (b) sensors in G-Specimens.

4.2. Functionality of embedded transducers

As previously mentioned in paragraph 3.4, the capacitance of the embedded transducers in three G-specimens was measured at the pristine and impacted state of the samples, and then at 120, 240, 360 and 480 thousand cycles of fatigue testing. Capacitance measurements and nonlinear ultrasonic experiments were not conducted beyond 480 000 cycles as the test specimens were severely damaged. The results for both the transmitting and the receiving PZTs were summarised in figures 10(a) and (b) respectively, indicating that the capacitance was as 1.54 ± 0.02 nF at all different states of composite samples. This suggested that PZT transducers remained functional at least up to 480 000 cycles, which is nearly 70% of the fatigue life of undamaged composite samples used in this study. In addition, these capacitance measurements verified that the data from the ultrasonic experiments described in section 3.5, were acquired using undamaged sensors.

4.3. Nonlinear ultrasonic testing results

The above G-specimens were used in nonlinear ultrasonic experiments following the procedure explained in section 3.5. After examining the received signal spectrum in each test sample, the highest amplitude of A_2 harmonics corresponded to an input frequency range of 200–220 kHz. That was reasonable since the 200–220 kHz range was close to the radial resonance frequency of the PZT transducers (~ 300 kHz), meaning that the energy of propagating waves should be relatively high. By plotting the value of parameter β ($\propto A_2/A_1^2$) across that range, it showed that the material damage was excited strongly at the driving frequency of around 210 kHz. According to figure 11 below, the value of β in all three cases was found to increase from the pristine to the impacted state of samples and, then, every 120 000 loading cycles. This behaviour of β was expected because the material damage was also increasing. For clarity, the peak value of β was plotted at each state of the G-specimens (figure 12), showing a consistent increase of about 0.07×10^{-3} to 3×10^{-3} . It is worth noting that β was not equal to zero at the pristine state of the samples, because low-amplitude A_2

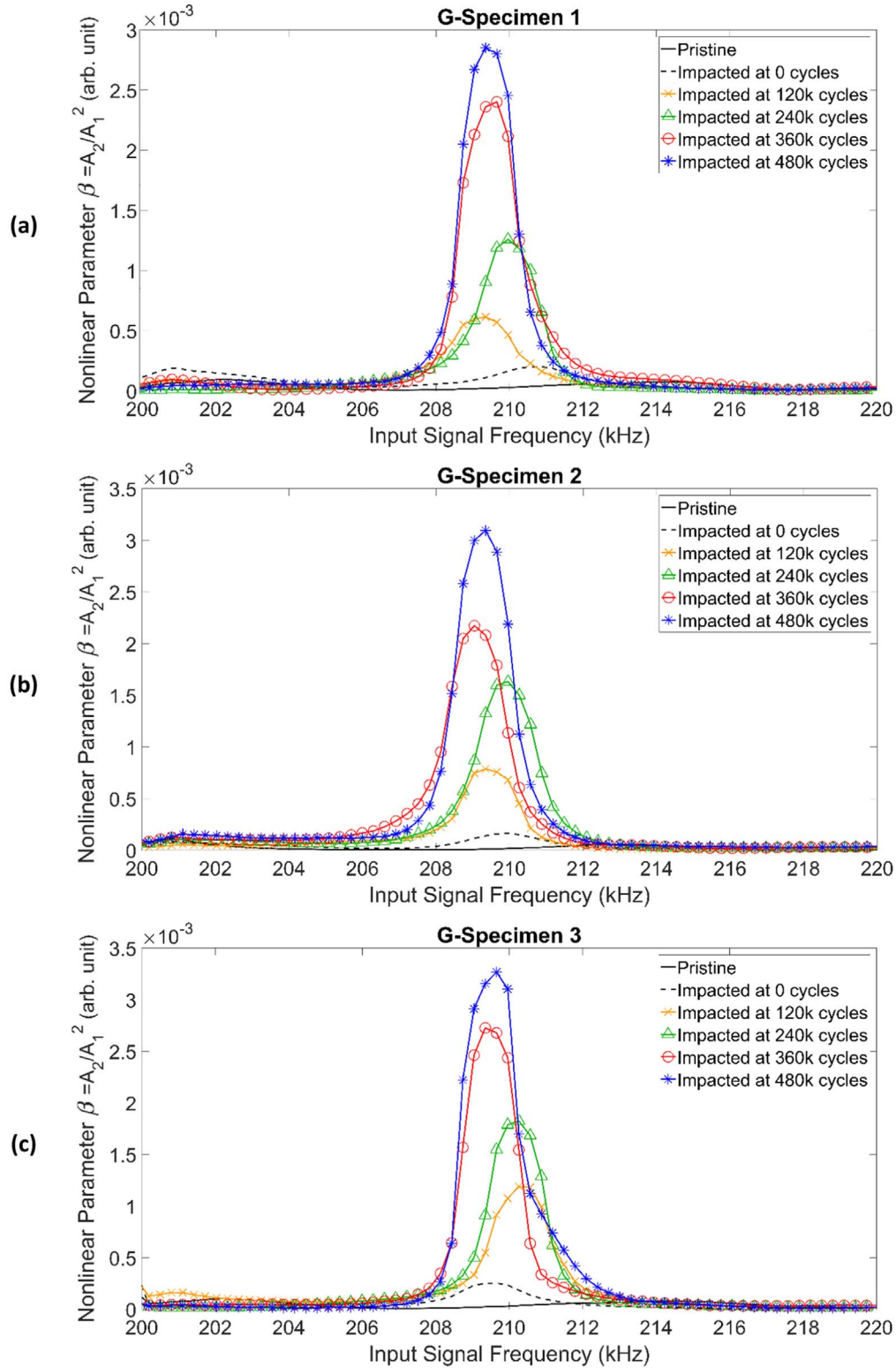


Figure 11. Change in nonlinear parameter β with increasing number of fatigue cycles for G-specimen 1 (a), G-specimen 2 (b) and G-specimen 3 (c)—input signal of 100 V at 200–220 kHz.

harmonics were present in the receive signal spectrum. This could possibly be attributed to instrumentation noise, since the initial value of β was almost identical in all three G-specimens. Moreover, it is must be noted that high repeatability was observed in the increase of β ($\sim 0.2 \times 10^{-3}$)

between the pristine and the impacted state, and that was reasonable considering that the test specimens were initially damaged using the same impact energy of 3 J. From the impacted state and up to 480 000 cycles, the rising trend of β contained small fluctuations, but that was also expected

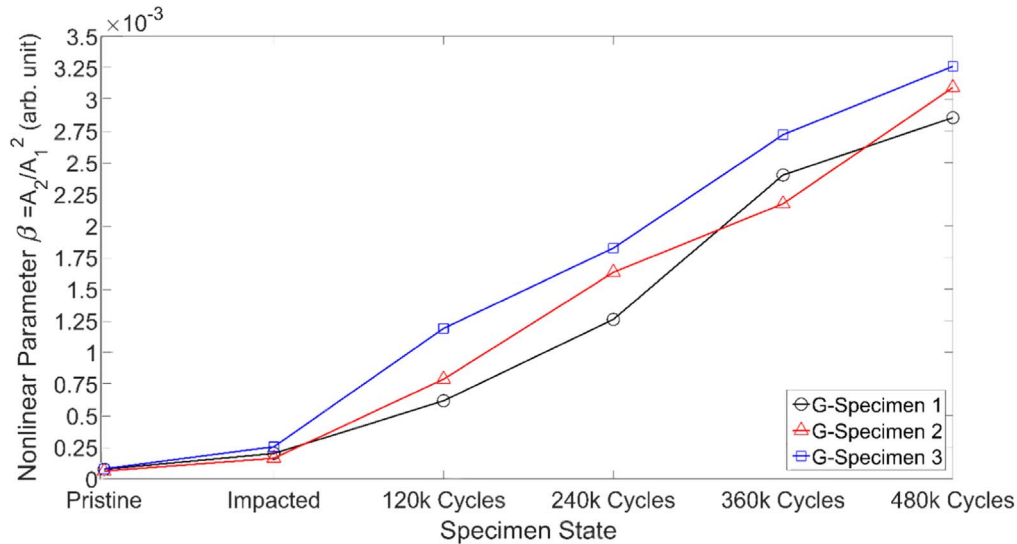


Figure 12. Peak value of nonlinear parameter β at each state of G-specimens 1, 2 and 3 during fatigue testing—input signal of 100 V at ~ 210 kHz.

because the shape and size of damage in composite laminates could not change linearly and uniformly as in isotropic materials (e.g. metals). The above results proved that except for BVID detection, this novel arrangement of internal PZT disks was capable of monitoring the growth of material damage for more than two-thirds of the mean sample life ($\sim 713\,000$ cycles).

5. Conclusions

This study assessed the tensile strength and the fatigue endurance of a recently developed design of ‘smart’ CFRP composite plates containing internal PZT transducers that were covered with glass fibre patches for electrical insulation. Specifically, CFRP samples with two embedded sensors (G-specimens) were tested against plain samples (P-specimens). The tests were performed using undamaged specimens of each group, as well as specimens with BVID caused from low energy (3 J) impacts. The ultimate tensile strength of the P- and G-specimens was similar in both tests; ~ 910 MPa for undamaged samples and ~ 865 MPa for impact damaged samples. Based on these values, the specimens of each group with and without damage were subject to tension-tension fatigue testing at a stress level ranging from 8% to 80% of the associated material strength. Again, the P- and G-samples failed on average at the same number of cycles, which was around 713 000 for the pristine samples and 675 000 for the damaged samples. The test data obtained from P-specimens were statistically compared to those of G-specimens using a standard one-way ANOVA. This analysis indicated that the pristine P- and G-samples had equal mean values of maximum tensile strength ($p = 0.57$), maximum extension ($p = 0.83$) and fatigue cycles to failure ($p = 0.55$). The same outcome applied to the case of impact damaged samples and the corresponding p -values were 0.41, 0.70, and 0.64. These results suggested that the proposed configuration of internal

PZT disks had not reduced the tensile strength or the fatigue endurance of the ‘smart’ CFRP composite. In addition, the failure mode of the tensile test samples was central through-thickness shear, whereas in the fatigue test samples experienced central explosive failure. It must be noted that the failure type in both tests was the same between the undamaged P- and G-specimens and between the impacted P- and G-specimens. This revealed that the damage propagation in G-samples had not changed by the existence of internal sensors. Moreover, during fatigue testing, nonlinear ultrasonic experiments were conducted on three impacted G-samples, to examine the ability of the internal sensors to monitor the evolution of BVID with increasing number of loading cycles. These experiments were performed before and after impacting the G-samples, and then every 120 000 cycles. In each specimen, one PZT was used for the transmission of elastic waves ranging from 80 kHz to 600 kHz, and the nonlinear parameter β was calculated from the A_1 and A_2 amplitudes received by the second PZT. The data acquired at a driving frequency of 210 kHz showed that between the pristine and the impacted state of the samples, β raised by approximately 0.2×10^{-3} , and then continued to increase (up to $\sim 3 \times 10^{-3}$) until the samples completed a total of 480 thousand fatigue cycles. After that point, nonlinear ultrasonic testing stopped because the composites were severely damaged. The change in parameter β was very similar between the tested G-specimens proving that the specific arrangement of embedded PZT disks could not only be used for the detection of BVID in CFRP composites, but it was also capable of monitoring the increase in damage size. Finally, at all stages of ultrasonic data acquisition up to 480 000 cycles, the capacitance of the sensors was about 1.54 nF verifying that the PZT transducers remained functional for at least 70% of the specimen’s life. The above results suggest that future solutions for on-board ultrasonic inspections of aerospace structures could possibly rely on SHM systems consisting of composite panels with embedded PZT

transducers, similar to the ‘smart’ CFRP composite design presented in this work.

ORCID iDs

Michele Meo  <https://orcid.org/0000-0003-1633-8930>

Francesco Ciampa  <https://orcid.org/0000-0003-3846-8891>

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