Evaluation of the sensitivity and fatigue performance of embedded piezopolymer sensor systems in sandwich composite laminates

N A Chrysochoidis and E Gutiérrez

European Commission, Joint Research Centre (JRC), Institute for the Protection and Security of the Citizen (IPSC), European Laboratory of Structural Assessment, Via Enrico Fermi 2749, 21027 Ispra VA, Italy

E-mail: nikolaos.chrysochoidis@jrc.ec.europa.eu

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Abstract

It has been claimed that embedding piezoceramic devices as structural diagnostic systems in advanced composite structures may introduce mechanical impedance mismatches that favor the formation of intralaminar defects. This and other factors, such as cost and their high strain sensitivity, have motivated the use of thin-film piezopolymer sensors. In this paper, we examine the performance of sandwich composite panels fitted with embedded piezopolymer sensors. Our experiments examine both how such thin-film sensors perform within a structure and how the inclusion of sensor films affects structural performance. Strain-controlled tests on sandwich panels subjected to three-point bending under wide-ranging static and dynamic strains lead us to conclude that embedding thin piezopolymer films has no marked reduction on the tensile strength for a wide range of strain loading paths and magnitudes, and that the resilience of the embedded sensor is itself satisfactory, even up to the point of structural failure. Comparing baseline data obtained from standard surface-mounted sensors and foil gauges, we note that whereas it is possible to match experimental and theoretical strain sensitivities, key properties—especially the pronounced orthotropic electromechanical factor of such films—must be duly considered before an effective calibration can take place.

Keywords: piezopolymer, sandwich composites, fatigue, embedded sensor, sensor sensitivity

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

1. Introduction

Advanced composites are increasingly being used in an ever-wider range of structural applications, and they are often promoted as one of the preferred host materials for sensor diagnostic systems. Composite materials’ apparent ability to host all manner of sensors promotes them as key candidates for so-called smart structures. However, we are still far from fully understanding the effect of the sensor on the host’s structural performance and, conversely, the effect of the structure on the sensor’s metrological capacity.

An embedded device in a composite structure generates a discontinuity that may affect its structural integrity. Thus, the placement of the sensor can be considered as an inclusion that not only results in the net area loss of the material, but may also generate additional interlaminar stresses at or near the discontinuity within the host composite structure. This may result in a reduction of the load-carrying capability.

The selection and integration of diagnostic and actuation devices within structural composites is as varied as their applications, including piezoceramics, piezopolymers, fiber...
optics, shape memory alloys, strain sensors, and, more recently, the potential of creating a smart matrix system based on the use of nanoparticles. Lead zirconate titanate has attracted the greatest attention in a wide range of sensor forms and materials (Crawley and De Luis 1987, Warkentin and Crawley 1991, Chow and Graves 1992, Bronowicki et al 1996, Shukla and Vizzini 1996, Mall and Coleman 1998, Hansen and Vizzini 2000, Yocum et al 2003, and Tang et al 2011).

In our study, we focus only on the use of polymer piezoelectric devices, with a goal of understanding the dual sensor-structure performance and functionality when exposed to high strains in both static and fatigue loading. In particular, we are interested in how the process of embedding larger polyvinylidene fluoride (PVDF) piezopolymer films within the composite affects the laminate performance and, conversely, how the sensor is affected by being embedded in the structure and how it copes with sustained high-strain excursions.

Another aspect of our study concerns more specific metrological aspects, such as the theoretical versus experimental piezopolymer strain sensitivity, material orthogonality, and the potential of piezo-polymer to be used as low-cost, low-maintenance, multifunctional measurement and diagnostic systems.

PVDF is manufactured in so-called single-axial and biaxial piezoelectric forms (i.e., isotropic and orthotropic). A calibration process must therefore consider whether—depending on the compliance properties of the host composite material—the type of PVDF used will significantly affect the calibration factors (Sirohi and Chopra 2000). As we will show, when PVDF sensors are incorporated into highly anisotropic composite layups, the effect of the host material’s Poisson ratio or the orientation of the piezofilm in the predominant principal stress plane may couple the orthotropic piezoproperties with unexpected results.

The potential of using piezoelectric polymer films as monitoring devices in composites followed soon after their discovery in the late 1960s (Kawai 1969, Shufford et al 1977) pointed to both the potential and orientation aspects of PVDF films as alternatives to standard strain gauges for monitoring composites. In relation to the calibration of PVDF sensors as alternatives to foil strain gauges, Sirohi and Chopra (2000) considered how this aspect should be factored into the correction elements. Failing to consider piéo-orthotropy can result not only in passive measurement errors, but also in dynamic effects whenever the sensors are used as actuators, as shown in the study by Sokhanvar et al (2007). The number of investigations in the literature concerning the experimental evaluation of PVDF material properties is somewhat limited, but the study by Roh et al (2002) and the more recent study by Seminara et al (2011) suggest that the ratios of the piezostain coefficients in the orthogonal plane to the poling direction can, depending on the manufacturer, be up to nearly one order of magnitude.

Schaah et al (2007) and Ghezzo and Nemat-Nasser (2007) examined the three-point bend fatigue performance of laminates fitted with embedded sensors. Caneva et al (2007) and De Rosa and Sarasini (2010) studied the performance of embedded PVDF sensors as acoustic emission devices. Meng and Yi (2011) used embedded PVDF sensors to study the impact performance of concrete under impact testing. The conclusions from the results of these studies vary widely, primarily because the interface between the sensor and the host’s matrix is a fundamental issue. However, in these studies, the use of PVDF films sandwiched between silver-ink electrodes within epoxy-based laminates appears to produce good interface results. In our study, we will follow up on some of the performance aspects pointed out in other studies, noting that we use the same type of PVDF products and comparable resin systems.

2. Theoretical background

Using the nomenclature given by Elvin et al (2001 and 2003), the constitutive equations for the vector resultant of a piezo-mechanical system are given by:

\[
\{D\} = \begin{bmatrix} ε^E \\ -ε^T \end{bmatrix} \begin{bmatrix} ε \\ E \end{bmatrix} = \{E\},
\]

where \(D\) is the electrical field-displacement vector, \(ε\) is the absolute permittivity matrix of the PVDF material (diagonal), and \(E\) is the applied electric field (vector). The mechanical components are: \(σ\) is the resultant stress vector, \(c\) is the stiffness matrix, and \(S\) is the applied strain vector. Superscripts \(S\) and \(E\) indicate that the strain and electric fields, respectively, are constant (preferably zero) when measuring the permittivity and stiffness matrices. In practice, due to material coupling and the fact that the system is usually part of an electronic component, these conditions are not actually met. For the moment, we consider these effects as being of second order. The term \(ε\) is the electromechanical coupling coefficient matrix; in other words, \(ε\) represents the transduction from mechanical to electrical energy. For the case of simple strain field in direction 1, equation (1) simplifies to

\[
\{D_3\} = \begin{bmatrix} ε^T_s \\ -ε_31 \end{bmatrix} \begin{bmatrix} E_3 \\ S_1 \end{bmatrix}.
\]

Single-subscript terms are either vectors or material constants that only have components in the stated direction (e.g., diagonal matrices like \(ε\)). The directionality of doubled subscripted terms is as follows (see figure 1(a)): The first subscript refers to the electrical directions and the second to mechanical. Thus, for example, \(d_{31}\) quantifies the induced polarization charge in direction 3 due to a unit stress in direction 1.

Assuming open-circuit conditions (i.e., \(D_3 = 0\)), the applied stress, \(σ_1\), through the electromechanical coupling term, \(ε_{31}\), generates positive and negative charges, \(q^±\), on either side of the film faces, resulting in the field \(E_3\). Thus, we
now have the situation shown at the bottom of Figure 1, so that

$$E_3 = -\frac{d_{31}\sigma_3}{\varepsilon_3^v}, \quad (3)$$

where $d_{31}$ is the piezoelectric constant given by $d_{31} = e_{31}/Y$. If we assume that during this process, the thickness, $t$, of the PVDF film is constant, and expressing the electric field as the ratio of voltage potential, $V$, over the distance of the electrodes, $t$ (i.e., $-E_3 = V/t$), then we have that

$$V_3 = \frac{d_{31}\sigma_3 t}{\varepsilon_3^v}, \quad (4)$$

which simply states that the voltage across the capacitor is proportional to the cross-sectional stress times the thickness of the PVDF film. The factor $g_{31} \equiv d_{31}/\varepsilon_3^v$ is usually quoted by manufacturers of piezofilms as a material property, and is usually referred to as the piezoelectric constant, with units $(V/m)\sqrt{N/m^2}$; in other words, it quantifies the electric field for every unit of stress applied. Now, for an even more intuitive description, one can simplify further by putting $\sigma = YS$ (where $Y$ is Young’s modulus), so one can now write

$$V = k_p S; \quad \text{where } k_p = g_{31}Yt. \quad (5)$$

Here one can draw an analogy with mechanical systems, so where we usually say that the force in a spring is the resultant of a displacement times its stiffness, one can say that the voltage across a sensor/capacitor is proportional to the piezomechanical stiffness, $k_p$, times the applied mechanical strain. This formulation is very convenient, as it permits derivations for voltages in terms of the physical constants and the observed strain field. This, in turn, clarifies the duality of piezosensors as both energy-transduction devices and self-actuated sensors, all in one package.

### Table 1. Electromechanical properties of the PVDF materials we used.

| Property                      | Value         |
|-------------------------------|---------------|
| Young’s Modulus (Y)           | GPa           | 2–4           |
| Yield strength                | MPa           | 45–55         |
| Relative permittivity ($\varepsilon_0$) |              | 12            |
| $d_{31}$ (charge mode piezoelectric coefficient) | C/N           | $23 \times 10^{-12}$ |
| $g_{31}$ (voltage mode piezoelectric coefficient) | Vm/N          | $216 \times 10^{-3}$ |
| Pyroelectric coefficient      | C/N m$^{-2}$  | $30 \times 10^{-6}$ |
| Density                       | Kg m$^{-3}$   | 1780          |

These equations are formulated in the open-circuit voltage format. However, there are equivalent formulations for the closed-circuit format, in which case the applied strains are expressed in terms of a charge buildup between electrodes.

We characterize the efficiency of a piezoelectric device by monitoring the experimentally measured strain sensitivity as a function of static and dynamic strains, and we compare these to nominal theoretical values. Here we define sensitivity as the average strain required to produce 1 volt over its effective surface. This quantity is reported here in $\mu$strain/volts; thus, a 10 $\mu$strain/volt sensor is more strain-sensitive than a 100 $\mu$strain/volt sensor. The inverse ratio defines the device as an actuator. As we will see, piezopolymer sensors are sensitive dynamic strain gauges, but poor actuators (especially as they have a relatively low elastic modulus).

Based on the electromechanical properties illustrated in Table 1 for each of the sensors, the sensitivity range can be calculated according to the equations above, assuming that $Y = 2$ GPa and the piezoelectric stress constant was $g_{31} \approx 0.216 \text{ Vm N}^{-1}$; given that the sensors tested had a thickness of 28 $\mu$m, the sensitivity for each of the PVDF devices was in the range of $\text{Sensitivity}_{\text{PVDF}} = 40 \sim 80 \mu\text{strain/volt}$. The second piezostress constant, $g_{32}$, is not explicitly provided by the manufacturer’s documentation, nor was the alignment of the $g_{31}$ direction in the plane of the PVDF film evident from the films. As we will show, this can have a pronounced effect on the resulting output voltages.

#### 3. Specimen preparation, materials, and sensors

The specimens tested were fabricated at our laboratory. They consisted of glass-fiber-reinforced polymer (GFRP) sandwich panels fitted with both embedded and surface-mounted piezopolymer sensors and films. The manufacture was conducted at room temperature using the vacuum-assisted resin infusion methodology—specifically, layers of 0/90 fabric cloth (205 g m$^{-2}$) infused with epoxy resin over a closed-cell foam core. The lamination configuration was [(0/90)$_{6}$/Core]$_{S}$. A low-volume-fraction GFRP system was selected to visually track the transducers in the specimens and (because it is nonconductive) the ease of electrically wiring the transducers located inside the plates. The epoxy resin system, the core materials used, and their properties are given in Table 2.
Three different types of piezopolymer devices were used, all manufactured from poled 28 μm-thick PVDF. Surface-mounted sensors with and without a protective 88.5 μm-thick biaxially oriented polyethylene terephthalate coating were used. The active electrode surface area of the patch sensors was relatively small (30 × 12.19 mm²), and we will show that it can be used as a dynamic strain gauge. For embedding applications within the thickness of the composite laminate (i.e., between two successive composite plies), a larger film sheet of 190 × 130 mm² was used without protective film, ensuring direct contact between the silver-ink electrode and the layers of glass-fiber reinforcement. The electromechanical properties of the PVDFs are summarized in table 1.

We manufactured two sandwich composites of dimensions (L × W × T) 280 × 100 × 34 mm³. During the fabrication of the panels, the large piezopolymer film sheet was placed at the penultimate layer of the sandwich skin laminate, toward the outer side of the sandwich composite. In other words, the film was as near as possible to the outer surface of the laminate while still being covered by one layer of glass reinforcement. Moreover, the film was folded over along the longitudinal direction over an area of 190 × 65 mm². This design was motivated by two factors:

1. The width of the unfolded film was wider than the width of the sandwich panel, and cutting the film in half while preserving the integrity of the electrodes was not feasible. Folding it allowed us to fit it within the specimen’s width and preserve the electrical functionality.

2. One aspect of our study concerns the potential of embedding sensors for energy-harvesting applications. Given that the voltage is proportional to the effective strain, folding a film would be equivalent to placing two sensors of half the width over the same strain field, which optimizes the strain energy capture field.

To improve the flow of the resin infusion between the folded PVDF layers, an extra distribution ply was inserted between the two faces of the folded sensor, as illustrated in figure 2. The folded sensor was placed at the penultimate layer of the composite laminate nearest the surface. The electrodes of the folded sensor were connected to fine wires that pass, through thickness, out of the laminate and exit normal to the panel surface. For material property repeatability, both specimens were fabricated in a single resin infusion batch. Both specimens exhibited similar composite skin thickness and quality, indicating a uniform resin infusion process. However, there was a minor difference in the specimens: The location of one of the large film sensors shifted by 2 mm with respect to the center line. Otherwise, the sensor type and dimensions were nominally equal. To monitor and eventually calibrate the piezopolymer-based sensors, three unidirectional, 350 Ω, 10 mm × 30 mm strain gauges were positioned in a row along the length of the specimen surface. The first was closely located between the two piezopolymers, and the other two were located 85 mm away from the mid-length. The configuration of specimen S1, with the locations of both the piezopolymers and the strain gauges, is illustrated in figure 3.

### 4. Experimental method

The experimental campaign consisted of cyclic testing in a three-point bending configuration. The lower, tensile face housed all the PVDF sensors and strain gauges. The general procedure consisted of applying a dynamic load, combined with a static offset, at varying levels of amplitude. To monitor the effects of path sensitivity on fatigue capacity, two differing load combinations of cycle amplitude and static offset were chosen, but they were sequenced to arrive at the same cumulative service-history demand.

| Property       | Units | AT30 SLOW | Core material |
|----------------|-------|-----------|---------------|
| Density        | Kg m⁻³| 10.8–11.2 | 85            |
| Flexural strength | MPa | 112–124   |               |
| Tensile modulus     | MPa | 3.15–3.55 | 90            |
| Tensile strength       | MPa | 65.5–73.5 | 1.5           |
| Compressive modulus  | MPa | 70        |               |
| Compressive strength |     | 1         |               |
| Shear strength    | MPa  | 65.5      |               |
| Shear modulus    | MPa  | 124       |               |

*Table 2. Properties of the easy composites, AT30 (slow) epoxy resin, and the AIREX T92.90 core material.*

![Figure 2. Folded sensor placed at the penultimate layer of the composite laminate on top of the foam core. A layer of glass cloth was inserted between the two sides of the folded PVDF sensor.](image2)

![Figure 3. Foam core sandwich Specimen 1, with embedded piezopolymer film sheet and attached piezopolymers and strain gauges.](image3)
4.1. Experimental setup measuring and control equipment

The experimental setup is illustrated in figure 4. A 50KN MTS testing frame was equipped with a three-point bending tool, according to ASTM C393 bending testing standard specifications for composite materials (ASTM C393/ C393M 2012). The PVDF sensors and strain gauges were located on the tensile face of the three-point bending configuration, so they would not be damaged by the concentrated mid-span bearing loads on the compression face of the panel.

The signal conditioning and data were sampled using a National Instruments platform. For each test, there was synchronous acquisition of the voltage from each PVDF sensor, the applied piston displacement, and the resultant force, using an SCXI-1140 module. Simultaneously, the strains were recorded on an SCXI-1520 strain gauge conditioning module (quarter bridge configuration). The machine was operated in dual loop control, consisting of an outer loop in displacement control, which was in turn driven by an inner loop based on strain feedback from the central strain gauge mounted at the specimen’s mid-span. More specifically, the displacement loop was actuated by a proportional-strain-error feedback loop until the desired levels of strain (dynamic and static) were achieved. Computation of the strain-error loop signals was performed in Labview and was then used to generate a voltage signal from the analogue output of an NI-6229 board, which, in turn, drove the MTS controller (through the external-input source).

4.2. Dynamic range of piezodevices

Piezoelectric devices are also electrical capacitors, so their performance is highly frequency-dependent, with no direct current output. The application of a dynamic load generates a charge between the two electrodes on either side of the PVDF film, which then discharges with a time constant proportional to the capacitance and the resistive load. In effect, when piezoelectric polymer sensors are loaded with a parallel resistance, the capacitance and the resistive load. In effect, when piezoelectric polymer sensors are loaded with a parallel resistance, the capacitance of the device. The effect of this dynamic cutoff frequency is such that at static and low frequencies well below \( f_c \), the output generated by the device is proportional to the rate of change of strain (hence, very low electromechanical transduction). However, for excitations above \( f_c \), the output is constant for a given strain amplitude (i.e., a dynamic, self-excited strain gauge). The effective gains observed across the terminals of a PVDF sensor depend on the impedance mismatch of the sensor, the measuring device, and the frequency range of the phenomenon being measured. Because the input impedance of our measuring instrument is more than 1 GΩ, we can assume an open-circuit measurement on the input voltage. We will discuss this aspect further later in this paper.

PVDF sensors are floating (nonearthed) source voltages, so to avoid voltage drift from leakage currents when connected to measurement instruments, a resistance is connected in parallel to the sensor terminals. The magnitude of the resistance can also be chosen to tune the cutoff frequency; typically we chose 10 MΩ or 1 MΩ to optimize the output voltage for our experiments. The effect of the load resistance on the measured voltage (gain and phase) for each of the oscillation frequencies applied on the specimen is illustrated in table 3 and are plotted in figure 5.

4.3. Fatigue loading paths

Each specimen’s loading history was composed of seven individual static and dynamic loading steps. A static bending load was first applied up to a target mid-span strain level (as measured by gauge SG1). The second control parameter was defined by the magnitude of dynamic oscillation and was expressed as the standard deviation of the strain around the mean static strain. The static and dynamic strain parameters were controlled by sampling the data and making statistical calculations over 10 cycles. As previously mentioned, different loading paths were performed for each specimen, as illustrated in figure 6. In one scheme, we imposed a constant frequency and dynamic strain, \( SD(\varepsilon) \), while increasing the static strain offset, \( \mu(\varepsilon) \), followed by a final large increase in the fatigue amplitude to reach \( \varepsilon(\mu, SD) \). In the second mode, we gradually increased both fatigue and static amplitudes until we arrived at the same end point, \( \varepsilon(\mu, SD) \). Every individual point on the graph is described by the mean static strain, \( \mu(\varepsilon) \), and the standard deviation of the oscillation strain, \( SD(\varepsilon) \). The oscillation frequencies chosen were as follows: 5 Hz for Specimen S1, while the oscillation standard deviation remained constant at 100 μstrain, and 10 Hz for the remaining sets at a constant mean static strain of 4000 μstrain. For Specimen 2, the forcing frequency was 15 Hz for the total duration of the loading path. The total number of exercise cycles was just over 6 million for both specimens.

5. Results and discussion

5.1. Preliminary experimental assessment of sensitivity

Before undertaking extensive fatigue tests, and in order to compare to baseline data, both specimens were subjected to
three parametric sensitivity analyses. The first consisted of cyclic three-point bending tests of 1000–1200 cycles at frequencies ranging from 1–10 Hz in steps of 1 Hz, keeping the standard deviation of the strain amplitude of SG1 at 300\(\mu\)strain. The second consisted of three-point bending tests with increasing standard deviation of the strain amplitude in the range of 50–500\(\mu\)strain, with the oscillation frequency at 5 Hz. The third was the same as the second, but with the frequency set at 10 Hz.

In all parametric studies, the static offsets were in the range of 1000\(\mu\)strain. The full set of results for the embedded sensor is reported in Chrysochoidis et al (2013). The ensemble mean and standard deviations of the sensitivity measured for each of the sensors in all three parametric studies are given in tables 4–6. The data show that the sensitivity appears not to be greatly affected in the parametric range given above. For the small sensors, the sensitivity was calculated with respect to the strain recorded from SG1. For the larger, embedded film sheet, the sensitivity was calculated with respect to the average strain measured from all three strain gauges across the sensor length. We evaluated the average strain field, implying simple bending theory, from the individual strain gauges along the length, as \(\varepsilon = (2\varepsilon_1 + \varepsilon_2 + \varepsilon_3)/4\).

Whereas the correlation with the predicted values for the two small piezopolymer sensors lies in the range of the analytically estimated values (40 to 80\(\mu\)strain/volt), the larger (folded) embedded film sheet for both specimens presents a significantly lower average sensitivity than expected, varying between 180 and 200\(\mu\)strain/volt. The discrepancy cannot be trivially explained by the fact that by folding the sensor, the measured voltage is halved, as in principle, two films of half the width, when exposed to the same strain field, would measure the same voltage but would generate half the energy each. This is because by having their capacitance halved, but keeping all other factors equal, the piezocapacitance is proportional to the effective electrode area. Given that this discrepancy was repeatable—not only from one specimen to the next, but also for the full range of fatigue data—we conjectured that we had folded the film in the plane \(g_{32}\) and not \(g_{31}\).

To clarify the issue, we manufactured another specimen, S3, which was similar to the other two and consisted of a simple surface-mounted PVDF sheet with CU/Ni metallized electrodes from the same manufacturer, fitted with ready-mounted pin connectors, as shown in figure 7(a). On the specimen, we generated a constant strain over the length of the sensor in a four-point bending configuration. The results revealed that the measured sensitivity was 54\(\mu\)strain/V, which falls within the expected theoretical range. We contacted the PVDF manufacturer (personal communication with R. Brown, Measurement Specialties), who suggested a value for \(g_{32}\) in the range of [0, 35]\(\mu\)C/N. More importantly, we were informed that the principal stretching direction during poling was orthogonal to the folding axis of the embedded

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**Table 3.** Sensor voltage correction factor for two resistive loads (1 and 10 M\(\Omega\)) and three oscillation frequencies (5, 10, and 15 Hz).

| Resistive load (M\(\Omega\)) | Frequency (Hz) | Embedded film sheet (77 nF) | Miniature with protection coating (1.41 nF) | Miniature without coating (1.36 nF) |
|---------------------------|----------------|-----------------------------|---------------------------------------------|--------------------------------------|
| 1                         | 5              | 0.92                        | 0.04                                        | 0.04                                 |
|                           | 10             | 0.98                        | 0.09                                        | 0.09                                 |
|                           | 15             | 0.99                        | 0.13                                        | 0.13                                 |
| 10                        | 5              | 0.99                        | 0.39                                        | 0.41                                 |
|                           | 10             | 0.99                        | 0.65                                        | 0.66                                 |
|                           | 15             | 0.99                        | 0.79                                        | 0.80                                 |

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**Figure 5.** Effect of resistance on each of the sensors for oscillation frequency 5 Hz.

**Figure 6.** The two fatigue testing loading paths applied to Specimen 1 and Specimen 2, respectively.
folded films, which resulted in the much lower voltage obtained compared to the patch sensors (figure 2). It was also confirmed that the $g_{31}$ axis for the PVDF mounted on S3 coincided with the long axis of the sensor, as shown in figure 7(a)—hence the consistency of the strain sensitivity obtained for this configuration.

To further validate our findings, we conducted a four-point bend test using two orthogonally mounted patch sensors made from the same material as the large embedded film sheet and a three-direction strain gauge rosette, as shown in figure 7(b). The ratio between the measurements of the sensors’ voltages was $V_1/V_2 \approx 3.5$. Thus, applying this ratio to the folded sensor, the sensitivity in the $g_{31}$ direction is of the order of 55 $\mu$strain/volt, and hence coincides with the expected range.

Another aspect that generates a difference in performance is the use of a protective polymer coating. The presence of this coating appears to generate a pronounced hysteresis loop that is normally not present in the unprotected sensor. In figure 8, we show measurements taken during one representative cycle of the protected and unprotected sensors on specimen S1 when driven at 5 Hz. The red hysteresis loop captures the effect of the coating, whereas the response of the bare sensor appears to be completely linear. This

Table 4. Sensitivity factor and respective standard deviation of sensitivity for each sensor, for infinite input impedance on the input terminals ($^1$ in $g_{32}$ direction).

| Sensor          | Specimen 1 | Specimen 2 | Standard deviation (\(\mu\text{strain/volt}\)) |
|-----------------|------------|------------|-----------------------------------------------|
| Protective film | 51.6       | 62.3       | 1.6                                           |
| No protective film | 47.4     | 46.6       | 1                                              |
| Embedded$^1$    | 184.9      | 190.5      | 7.7                                           |

Table 5. Mean sensitivity and respective standard deviation for each sensor, for increasing oscillation standard deviation in the range 50 to 500 $\mu$strain when oscillation frequency was set at 5 Hz ($^1$ in $g_{32}$ direction).

| Sensor          | Specimen 1 | Specimen 2 | Standard deviation (\(\mu\text{strain/volt}\)) |
|-----------------|------------|------------|-----------------------------------------------|
| Protective film | 55.8       | 65.3       | 5.8                                           |
| No protective film | 52       | 48         | 8.6                                           |
| Embedded$^1$    | 184        | 194.5      | 8.1                                           |

Table 6. Mean sensitivity and respective standard deviation for each sensor, for increasing oscillation standard deviation in the range 50 to 500 $\mu$strain when oscillation frequency was set at 10 Hz ($^1$ in $g_{32}$ direction).

| Sensor          | Specimen 1 | Specimen 2 | Standard deviation (\(\mu\text{strain/volt}\)) |
|-----------------|------------|------------|-----------------------------------------------|
| Protective film | 55.2       | 59.6       | 1.65                                          |
| No protective film | 46.4     | 46.15      | 1.3                                           |
| Embedded$^1$    | 200        | 188.8      | 12.2                                          |

Figure 7. Foam core sandwich specimen S3 (a) bottom face with surface-mounted piezopolymer sensor covering the area 95 × 62 mm$^2$ and three strain gauges, and (b) top face with two miniature PVDFs.
phenomenon was also observed for specimen S2. The most probable reason of this hysteretic behavior is that the 88.5 μm coating layer generates nonlinear forces between the interface of the PVDF film and the composite laminate; the loss-coefficient manifests itself as a hysteresis loop in the voltage versus strain plane. This behavior clearly shows how the PVDF sensor response is sensitive enough to reveal the presence of any discrepancy in the direct load transfer. We monitored the time lag for both specimens as a function of oscillation frequency, and we noted a marked correlation to the oscillation period, indicating that the phase lag was frequency-independent and constant at approximately 50 mRad. We conjecture that this phenomenon is probably associated with shear lag through the protective coating material, rather than a viscoelastic effect. This phenomenon is probably present in the bare piezopolymers, but is probably so small that it was not discernable with the time-step resolution of our data acquisition, which was set at 1 kHz.

5.2. Fatigue loading

The testing procedure was performed according to the loading history reported in figure 6, but we note that in both cases, they merge after the first 6 million cycles (7 loading sets). The campaign consisted of individual, concatenated daily-fatigue experiments of about 10 h duration. Between each experiment, the specimen was completely unloaded. For specimen S1, the total loading history was divided into 50 daily experiments at 5 and 10 Hz (5 Hz up to four million cycles, and 10 Hz until specimen failure, as shown in figure 6), but we completed only 22 daily experiments for S2 because the loading frequency was increased to 15 Hz.

Sensor voltages may exceed input levels for electronic equipment, so to attenuate these voltages and eliminate the drift currents, a resistive load was placed in parallel; we used 10 MΩ for specimen S1 up to the completion of 4 million cycles, and 1 MΩ afterwards. For S2, the resistance was 10 MΩ up to the completion of 6 million cycles, and for the last loading set we decreased this to 1 MΩ. For all cases, the voltage attenuation correction coefficients presented in table 3 were used to obtain the effective voltage outputs.

Figure 8. Effect of sensor coating on the relative sensitivity measured on the two different sensors.

Figure 9. Fatigue failure modes: (a) top skin failure of Specimen 1, and (b) shear core failure mode of Specimen 2.

Both specimens failed in the range of 6.1 to 6.2 million cycles. The failure modes for each specimen are illustrated in figures 9(a) and (b), respectively. For both cases, failure was initiated by local crushing of the core material immediately below the central bearing roller, followed by localized shear buckling failure of the skins. The failure was not catastrophic, but rather was noted by the fact that the specimen was unable to provide sufficient stiffness to proceed with the control strains demanded. In other words, the central span began to drift downwards without any apparent increase in the applied load. Given this mechanism, we also conjecture that this was accompanied by a progressive shift of the neutral axis of the sandwich panel resulting from the damage to the localized crushing in the top bearing area. Further loading propagated the damage, resulting in the characteristic shear core failure visible in figure 9(b).

The sensitivity of each of the three piezopolymer sensors as a function of the number of cycles during the fatigue testing is presented in figures 10(a) and (b) for the embedded and the patch piezopolymers, respectively. Each point in the plots represents the mean sensitivity for every individual experiment. The sensitivities of each sensor presented only slight variations during the fatigue loading history, but the performance of the embedded piezopolymer film sheets was of particular interest, as they were introduced in the composite skin at the penultimate ply in folded form, which could potentially be a weak area for delamination initiation. The general trend for both specimens was that, with increasing duty cycles, the strain required to produce one volt increased, which could be indicative of some form of degradation in either the sensor, the laminate, or the interaction between the two. We conjecture that this effect results from the formation of micro-cracks at the tension face, which remain hidden and may lead to sensitivity degradation. This can potentially be considered as a local damage indicator for the sensor-covered area; other sensitivity factors, such as temperature, are assumed to be constant. However, embedded sensors were shown to be capable of operating and generating voltages up to the point of incipient core crushing, as seen in figure 10(a), accompanied by an increase to the strain/volt ratio of both.
specimens. The sensitivity of surface-mounted sensors is repeatable and falls within the expended range, but the scatter of the surface-coated sensors is evident in figure 10(b). What is also apparent is that, given the extensive strain range and high duty cycles, the capacity of such sensors to operate continuously exceeds the suggestions of some authors to limit working strain levels to the order of 150 $\mu$strain (Sirohi and Chopra 2000).

In figure 11, we present the sensitivity as a function of the dynamic strain, and we report the dynamic strain amplitude in standard deviation from the mean (i.e., the RMS amplitude minus the static mean). For the embedded film sheets shown in figure 11(a), the sensitivity as a function of dynamic amplitude appears to be only marginally affected by the loading path; for S1, the 20 $\mu$strain/volt jump corresponding to the increases in the static load shown in figure 6. The gradual change seems to be captured also by specimen S2, following the second loading path in figure 6. However, in spite of the noticeable path differences, both specimens performed similarly and tended to reach the same sensitivity values as they approached the merge point, $\epsilon (\mu = 4000 \mu \epsilon, SD_f = 800 \mu \epsilon)$, after which both specimens failed in approximately 100 and 200 kCycles for S1 and S2, respectively. These results seem to validate the repeatability of the specimen’s performance, and they indicate that the ultimate structural fatigue performance is not drastically affected by the loading history, but ultimately by the limiting structural load.

Turning our attention to the actual voltage output, in figures 12(a) to (b) we show the generated voltage as a function of the number of cycles. The embedded folded film sheet can, at most, generate voltages up to 2 volts even at the highest strains (figure 12(a)). This low voltage results from two factors: First, we have established that the strain field in bending is oriented in the $\varepsilon_{32}$ coefficient’s direction. Second, given the three-point bending configuration, the average strain field over the film length has reduced the effective average strain field, and hence the charge generated. The voltage levels recorded for the surface-mounted sensors, as seen in figure 12(b), are significantly higher, but we note...
again that the sensitivity range of those sensors fitted with the protective coating is prone to inconsistency, as evidenced by the greater variation in the slopes compared to the simple, untreated sensors.

6. Conclusions

In this study, we showed that piezopolymer sensors, either mounted onto or embedded into the laminates of sandwich panels, exhibit stable high-strain sensitivity for a wide range of static and fatigue strain loading. We also showed that it is possible to embed larger sheets of piezopolymer within the composite laminate during the manufacturing process, providing the host structure with the added potential benefit of a built-in energy-harvesting capability.

The electromechanical sensitivity measured for surface-mounted piezopolymer sensors falls within the expected range when piezo-orthotropy was factored into the analysis.

For all sensor configurations tested, the performance appeared to be stable in the range of 1 to 15 Hz, but the presence of even a thin layer of protective coating on the sensor results in a hysteretic strain-voltage response. This hysteresis manifests itself as an out-of-phase oscillation of the generated voltage as a function of the applied strain, and it was found that the phase lag is constant in the range of frequencies studied, indicative of a rate-independent hysteretic process, possibly shear lag.

Our experiments also revealed that if the sensors are well embedded or bonded onto the structure, they are not significantly affected by the fatigue-loading history (i.e., differing parametric combinations of static and dynamic strain amplitudes), and they can operate in significantly high-strain fields. However, the slight reduction of the sensitivity recorded as a function of the number of cycles is a possible consequence of the micro-crack formation on the tension-loaded face.

We should note that due to failure initiated on the compressive and not the tensile side of the sandwich, both the surface-mounted and embedded sensors were still active even after the catastrophic failure of the panel. This performance implies that the intralaminar bonding surface of the large, embedded piezopolymer film sheet was sturdy enough to ensure consistent shear transfer from the laminate to the sensor at high loading strains.

PVDF devices can potentially provide the requested voltage at low working strain levels to supply an energy-harvesting circuit at voltage levels of 3 to 6 volts, which are satisfactory for commercially available electronic energy-harvesting rectification circuits. However, given the biased piezoelectric coefficients and the rather low energy-transduction efficiency, the orientation of the films should be clearly identified to align the film along the optimal direction.

PVDF sensors have some drawbacks compared to piezoceramics, particularly regarding stability and sensitivity at higher temperatures. On the other hand, their low modulus, thinness, high strain-to-failure ratio, and lower cost offer some advantages when applied in conjunction with flexible structures and composite materials. The orthotropy of some PVDF films can also be exploited by ensuring that the piezoelectric coefficient normal to the measuring direction is minimized, thus reducing the complexity of calibrating the sensor for Poisson and direct-coupling effects. In this sense, PVDF films offer an advantage over piezoceramics, which, due to their homogeneous piezo-properties, may require both Poisson and shear-lag corrections. Finally, the high signal-to-noise ratio can easily be exploited by adapting PVDF sensors to low-cost energy-harvesting and data-acquisition sensors, once due care has been taken for appropriate impedance matching.

We conclude that for low-cost applications where multiple (hundreds) sensors are required for field monitoring, PVDF-based sensors, especially embedded systems, may provide a satisfactory solution for dynamic-strain monitoring.
and structural diagnostics without the requirement of an additional power supply.

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