A Comparison of Optical Sensing Systems with Piezo-Electric Sensors for Impact Identification of Composite Plates

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ABSTRACT

This paper proposes using Fibre Bragg Grating (FBG) and piezoelectric (PZT) sensors for impact identification. The main objective is to evaluate the ability of the state-of-the-art sensors to estimate the impact energy, using the results of the PZTs as a reference. This approach allows a fair comparison and overcomes the inherent variability of different test runs of the same measurement. The comparison of sensor technologies consists of evaluating sensitivity to features for impact energy estimation, signal strength, repeatability, directivity, and signal correlation. Small-mass impacts were applied to a square composite plate at different locations and energies. The energy was kept low enough to avoid damaging the panel. The PZT and FGB sensors were placed at the same locations but on either side of the panel to compare signals evenly. The results showed that the energy from the measured response reflects the impact energy level. Moreover, FBGs and PZTs had comparable responses and an apparent similarity in time response, besides consistency in the frequency domain. The higher sampling rate for the PZTs allows for the analysis of higher frequency bands, compared to FBGs, showing relevant amplitudes above 10kHz. Future work will focus on developing and validating a force reconstruction algorithm and defining the optimal sensor configuration.

INTRODUCTION

The primary concern about aerospace composites is barely visible impact damage (BVID) [1]. Under subsequent operational loads, BVID can compromise structural integrity and lead to premature failure [2]. Therefore, there is a need to develop more efficient monitoring techniques integrated into the structure to detect and characterise such damage to optimize maintenance efforts. The need for inspection depends on the energy of the impact. Although many researchers have used sensor readings as input to impact localisation algorithms, inverse analysis of the impact response that determines impact force and energy is still limited. Thus, the question arises regarding which sensor

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technology best suits the latter application.

The general requirements for impact identification sensor systems are accurate detection of changes in parameters related to impact energy (with preferably low sensitivity to environmental changes), reliable transmission of captured signals, minimum interference to the target structure, sufficient robustness to environmental and operational conditions (EOC), and ease of installation, integration and operation. Furthermore, sensors for aerospace applications should have additional capabilities such as small dimensions, low weight, durability, enhanced noise tolerance, low electro-magnetic signature, low power consumption, a reduced wire (or even a wireless) solution, and low costs. In this respect, fibre optic (FO) and piezoelectric (PZT) sensors are the most popular Structural Health Monitoring (SHM) sensor technologies for aerospace applications.

The advantages of piezoelectric (PZT) sensors are their small size, lightweight, high sensitivity, robustness and low power consumption. In addition, PZT transducers can be used as actuators and sensors [3]. However, despite their advantages, are susceptible to electromagnetic interference, rely on wired connections and on electrical signals and their operating temperature range is limited (up to 150°C) [4, 5].

Optical sensors are a promising solution for SHM applications due to their light weight, durability and reliability, robustness, low power consumption, immunity to electromagnetic interference (EMI), high sensitivity and relative ease of integration. FO sensors for SHM applications are discussed in [6–10]. In general, the working principle of optical sensor systems are interferometric, grating-based or distributed [5, 10, 11]. In all three methods, the axial displacement is the physical measurand to which the optical fibre is sensitive. Here, Fibre Bragg Grating (FBG) sensors are used. The FBG sensor is an optical fibre multiplexed with a narrow-band reflector consisting of uniformly distributed gratings on the optical fibre [5]. The sensing principle detects changes in the central wavelength of the FBG reflector due to a tensile or compressive strain of the fibre, i.e. a shift in the wavelength of the reflected light is produced. Bragg grating sensors function as wavelength-specific mirrors caused by periodic disturbances. Therefore, the Bragg wavelength is reflected in a narrow-band spectrum with a central wavelength. Fibre Bragg Grating (FBG) sensors are particularly suitable for capturing static or dynamic strains. However, FBG sensors have disadvantages like directionality and limited sampling rate, although high-frequency interrogation systems have become available [12].

In this paper, fibre Bragg grating (FBG) and piezoelectric (PZT) sensors are compared in their performance for impact identification. The PZT results are used as a reference to evaluate the impact energy estimation capability of the sensors. The sensor technologies are compared regarding their (1): sensitivity (normalised transmitted impact energy; repeatability; signal strength); (2): directivity dependence; and (3): correlation. The transmitted energy [13] is the signal feature used to compare the signal response to different impact energies. The transmitted energy is assumed to be proportional to the area under the absolute value of the time domain curve for each sensor [13]. For example, Figure 1 shows the original signal ($y(t)$), based on which the transmitted energy E arrived at the sensor is calculated as:

$$E = \int_{t=0}^{t_{\text{end}}} |y(t)| \, \mathrm{d}t \tag{1}$$

Note that the time limits can be set from $t = 0$ to the end of the measurement time or the moment that the signal has dropped below a predefined threshold.

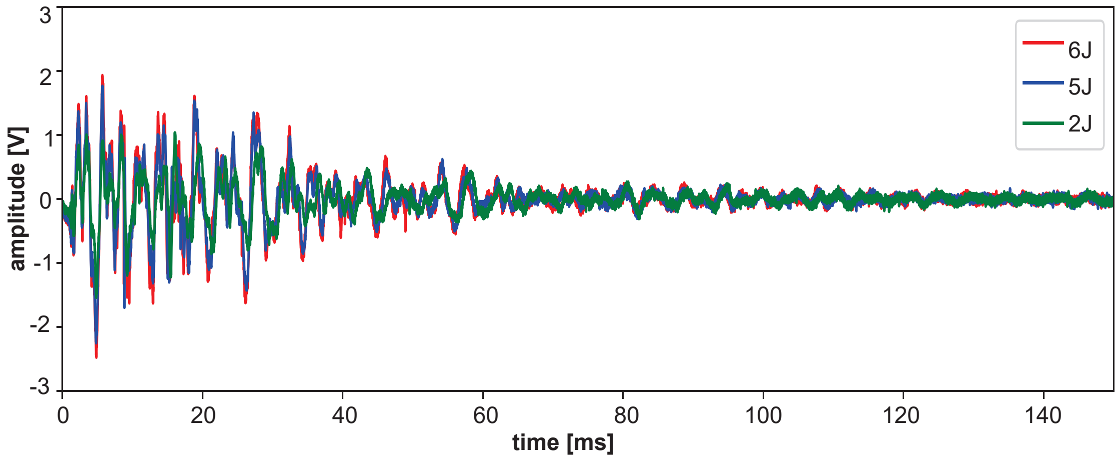

Figure 1. Original signal recorded by PZT6 sensor due to impact events of 2.0, 5.0 and 6.0J at impact location I4

EXPERIMENTAL SET-UP

Table I shows the mechanical properties of the thermoplastic composite panel made of Toray Cetex® TC1320 PEKK AS4D with a quasi-isostatic lay-up of 24 layers $[-45, 0, +45, 90]_{3s}$ and a ply thickness of 0.14 mm. Six piezoelectric (P-876 DuraAct Patch Transducer) and a single fibre with six FBG sensors were mounted on the test structure. The measurements were performed with the data acquisition systems USB Oscilloscopes Handyscope HS6 + HS5 and PhotonFirst interrogator for PZTs and FBGs, respectively.

Small-mass impacts [14] were applied to the square composite plate (960×960×3.55 mm) with an impactor of 16 mm head diameter and 0.5 kg mass at 13 locations (I1 to I13) and with three impact energies (2.0, 5.0 and 6.0 J) using a drop tower. Figure 2 shows the experimental design and setup.

TABLE I. Mechanical properties of Toray Cetex® TC1320 PEKK AS4D [15].

Density ρ [kg/m^3]	**Tensile Modulus 0°** E_1 [GPa]	**Tensile Modulus 90°** E_2 [GPa]	**In-Plane Shear Modulus** G_{12} [GPa]
1590	135	10	5.2

RESULTS AND DISCUSSION

The sensor technologies were compared in terms of their performance and metrological parameters. Therefore, the following analyses were performed:

(1) **Sensitivity test**: Normalised transmitted energy, repeatability and signal strength;

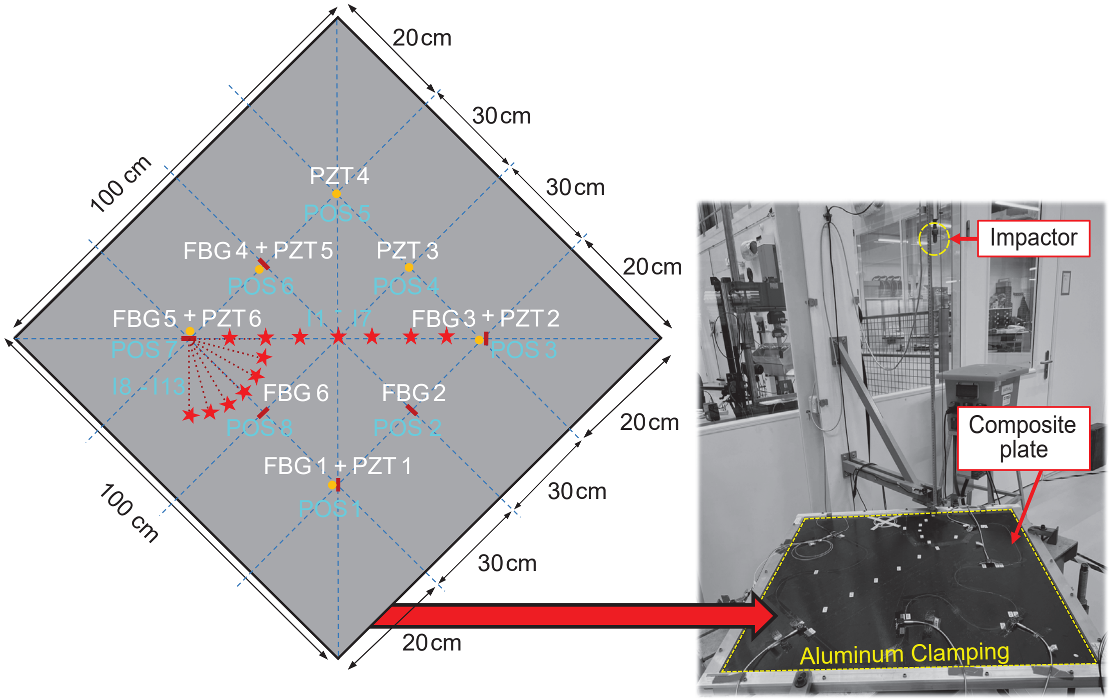

Figure 2. Test setup and schematic experimental design (▬ FBG • PZT ★ Impact Locations).

(2) **Directivity test**: Normalised transmitted energy for varying incident angle;

(3) **Correlation test**: Comparison of signal response in time- and frequency-domain.

Since optical systems and electrical signals differ in nature, some remarks and definitions are necessary. Measured responses are proportional to the energy transmitted, have different physical units, and are scaled differently. Optical signals result from changes in optical path length and have length units. In contrast, electrical signals are induced by the piezoelectric effect and have voltage units. Therefore, any quantitative assessment is normalised to unbiasedly compare performance and metrological parameters.

Sensitivity Test

Transmitted energy per channel: The two sensor technologies were compared using the normalised transmitted energy per channel. This parameter indicates the energy transmitted from a small-mass impact source and how it is distributed across the plate. This sensitivity test was performed by impacts at the central location (I4) with different impact energies (2.0, 5.0 and 6.0 J). Figure 3 shows that the normalised value for the transmitted energy increases with increasing energy for all sensor technologies. PZT and FBG sensors are comparably sensitive to transmitted energy and show consistency in normalised transmitted energy per location. However, the transmitted energy is not uniformly distributed across the plate, partly due to the direction of the propagating waves with respect to the ply orientation [16, 17] and the different distances to the sensors. Note that the distance to the sensors is greater at POS1, POS3, POS5 and

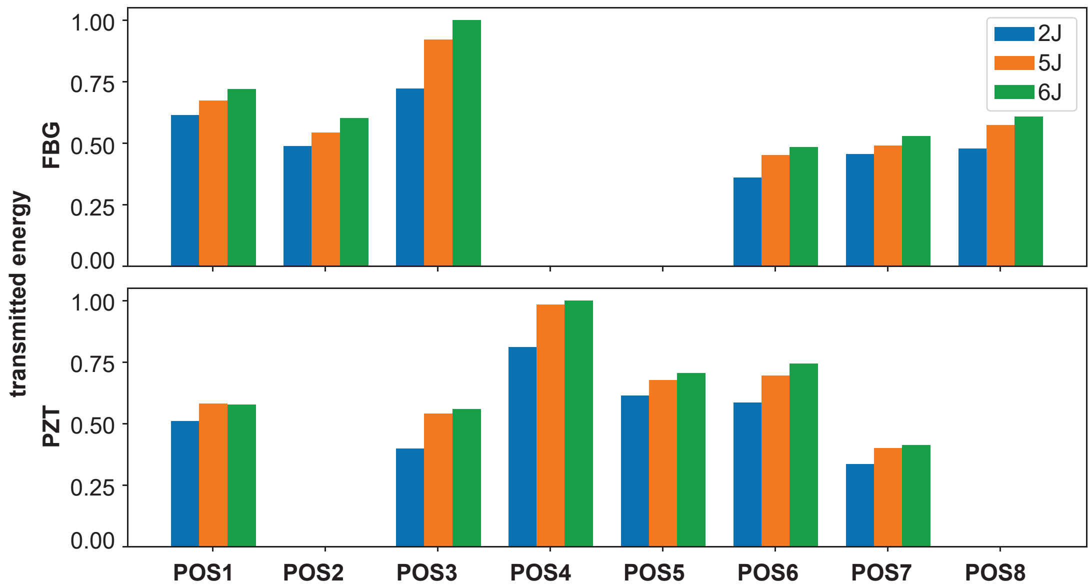

Figure 3. Bar plots of the normalised transferred energy due to impact events of 2.0, 5.0 and 6.0 J at I4 for FBG and PZT sensors.

POS7 than at POS2, POS4, POS6 and POS8 (see Figure 2). It is also expected that the sensitivity of FBG can be affected by the relative orientations of the wave propagation direction and the fibre axis [18, 19].

Repeatability: Repeatability was assessed by qualitative comparison of the waveform from repeated measurements. Three repetitions of waveforms recorded during a 6.0 J impact at I4 were considered for this analysis. Figure 4 shows the three time domain curves of the same setup for FBG (left) and PZT (right) sensors. For both sensors, high qualitative similarities between repeated waveforms are observed.

Signal Strength: The relationship between the normalised transmitted energy and the distance to the sensors is used to evaluate the signal strength of the PZT and FBG sensors at position POS7. Small-mass, 5 J impacts were recorded from these sensors at 7 evenly spaced locations (I1-I7) with increasing distance from the sensors. Figure 5

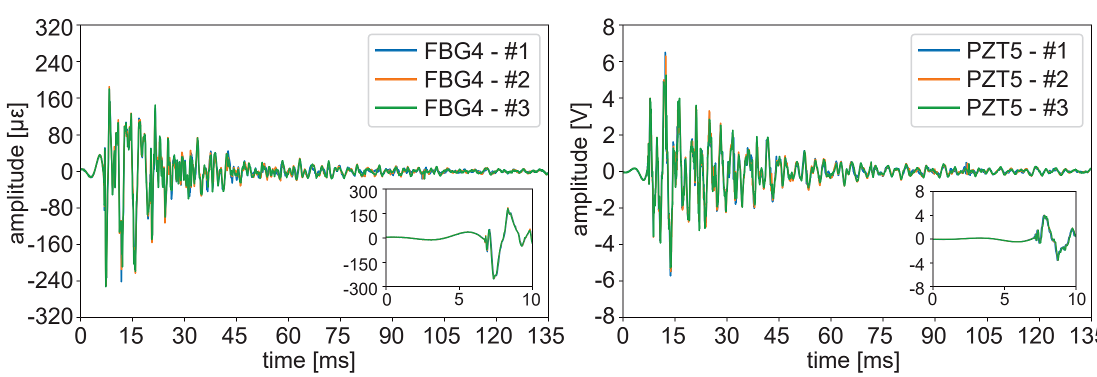

Figure 4. Three repetitions of waveforms recorded by FBG4 and PZT5 due to an impact event 5.0 J at I4.

shows that the normalised amplitudes of the transmitted energy of the PZT sensor decrease with increasing distance, according to the expected signal decay with increasing distance between impact and sensor. The same is true for the FBG sensor, which indicates consistency between the two sensors. The response measured for impact location I6 is an outlier for both the PZT and FBG, which hints at an issue with the execution of impact rather than the sensor readings.

Directivity Test

The dependence on directivity is an essential feature in detecting and characterising impacts. In the directivity tests, 5 J impacts were performed at seven uniformly distributed incident angles ranging from 0º to 90º (I2, I8-I13). The distance between the sensor position and the impact source was constant at 210 mm. The results in Figure 6 show a very close correlation between the directivity of the FBG and the PZT sensor for the energy-sensitive feature. Similarly, the standard deviation [20] of FBG5 and PZT6 sensors are low in each direction, so the directional sensitivities for measuring the normalised transmitted energy are consistent.

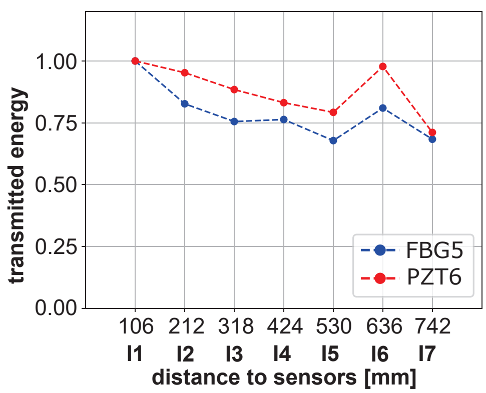

Figure 5. Normalised transmitted energy of 5J impact signal detected by FBG5 and PZT6 versus distance to sensors.

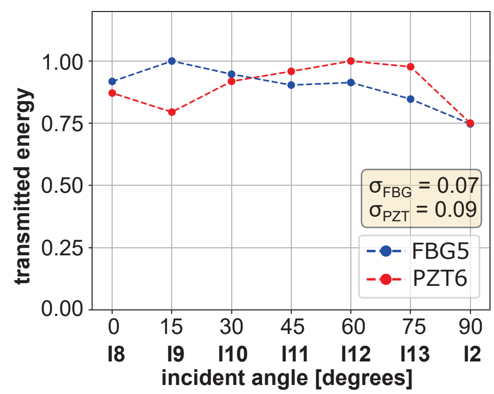

Figure 6. Normalised transmitted energy of 5 J impact signal detected by FBG5 and PZT6 versus incident angle.

Correlation Test

The correlation test aimed to qualitatively compare the waveforms of optical sensors with those of a PZT in the time- and frequency-domain. For this analysis, the signal was recorded by the sensors at location POS7, after an impact of 6.0 J at impact location I4. Figure 7a shows the measured waveforms in the time domain. The FBG and PZT signal response appear similar and shows a typical waveform expected from a small-mass impact source. Furthermore, the FBGs and PZTs had consistent frequency content (Figure 7b). Compared to FBGs, the higher sampling rate of PZTs enables the analysis of higher frequency bands with relevant amplitudes above 10kHz.

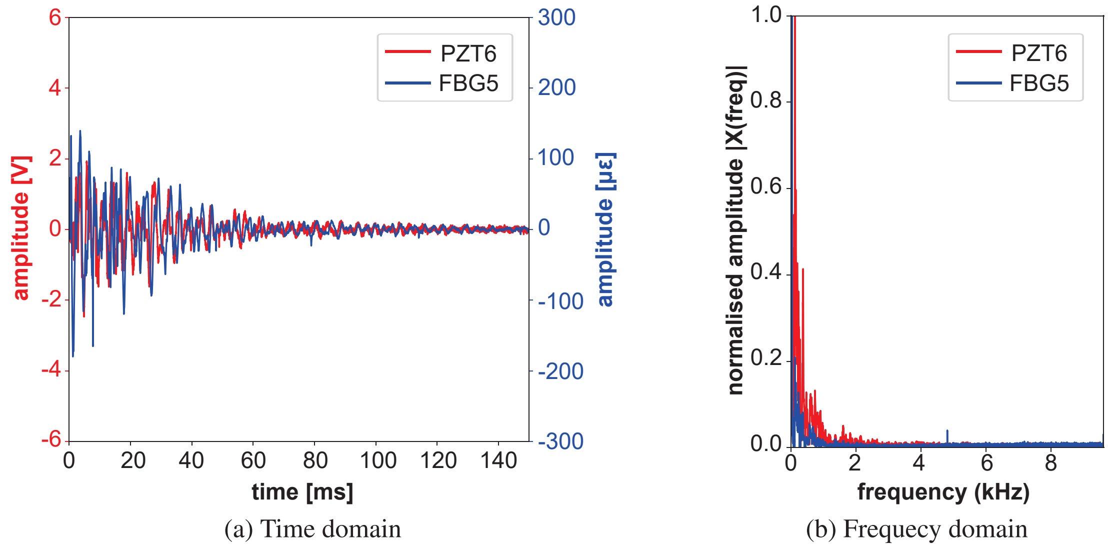

Figure 7. Comparison between FBG5 and PZT6 due to 6.0 J impact event at I4.

CONCLUDING REMARKS

Two types of sensors were investigated for their ability to estimate the impact energy in a composite plate. The results show that the energy transmitted to the plate from the measured response reflects the impact energy level for all two sensor technologies. In addition, FBG and PZT sensors respond similarly to transferred energy.

FBGs and PZTs showed appropriate repeatability and signal strength performance. The results showed similarities between the directivity of the FBG and PZT sensors. Accordingly, the directional sensitivities for transmitted energy measurement are consistent. The responses of FBGs and PZTs were comparable, presenting consistent time response and frequency content. In these first results, the limited sampling frequency of the FBG limits the assessment of accuracy, which is of great relevance to the estimation of impact energy.

Further research will be conducted to improve the understanding of fibre optic sensor readings and optimise the sensor arrangement, including an ultra-fast sampling interrogator to assess accuracy. In addition, geometrically more complex, full-scale horizontal tail aircraft component will be subjected to small-mass impacts.

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