Impact Identification Method for Structural Health Monitoring of Stiffened Composite Panels using Passive Sensing Systems

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Abstract. Identification of impact and its resulting damage is a complex inverse inferential procedure. Estimating the magnitude of an impact from sensor data is challenging and still needs to be fully understood. Furthermore, only a few studies have solved practical impact identification problems relevant to real-world structures with different geometries and structural inhomogeneities (e.g. variable thicknesses and stiffeners). Accordingly, the current research presents an impact categorisation analysis using passive measurements from piezoelectric (PZT) sensors for a geometrically complex composite aircraft part. Intermediate-mass impact tests were performed on a stiffened thermoplastic composite plate to generate signals representing various impact scenarios that may occur during the lifetime of an aircraft. The impacts were applied at critical locations, including the mid-bay, on top of the stringer, and at different thicknesses. This study investigated the effect of structural features on wave propagation in composite structures. The experimental results demonstrate that these features significantly change the wave field and, consequently, affect sensor readings. To differentiate between pristine and damaged states, an impact signal categorisation approach was employed. This analysis shows that a passive sensing system can categorise the impact using the transmitted energy from a time-domain signal. However, the spectral energy values showed low efficiency in categorising impacts. Overall, the results highlight the importance of considering structural features when deploying sensor systems for structural health monitoring and provide valuable insights into the effectiveness of impact identification and damage detection in realistic composite structures

Keywords: Impact Identification, Dynamics, Piezoelectric, Composites

Introduction

Structural Health Monitoring (SHM) has emerged as a critical research area in recent years due to the need for reliable and accurate condition assessment techniques. As composite materials are being widely used across different industries, impact identification and damage detection have become increasingly crucial in SHM systems [1]. Despite several advantages, composite materials are susceptible to barely visible internal damage (BVID) from impacts, which can lead to reduced structural integrity and, in some cases, catastrophic failure [2]. Therefore, impact identification is essential to ensure the safety, reliability and more realistic design scenario of composite structures [3].

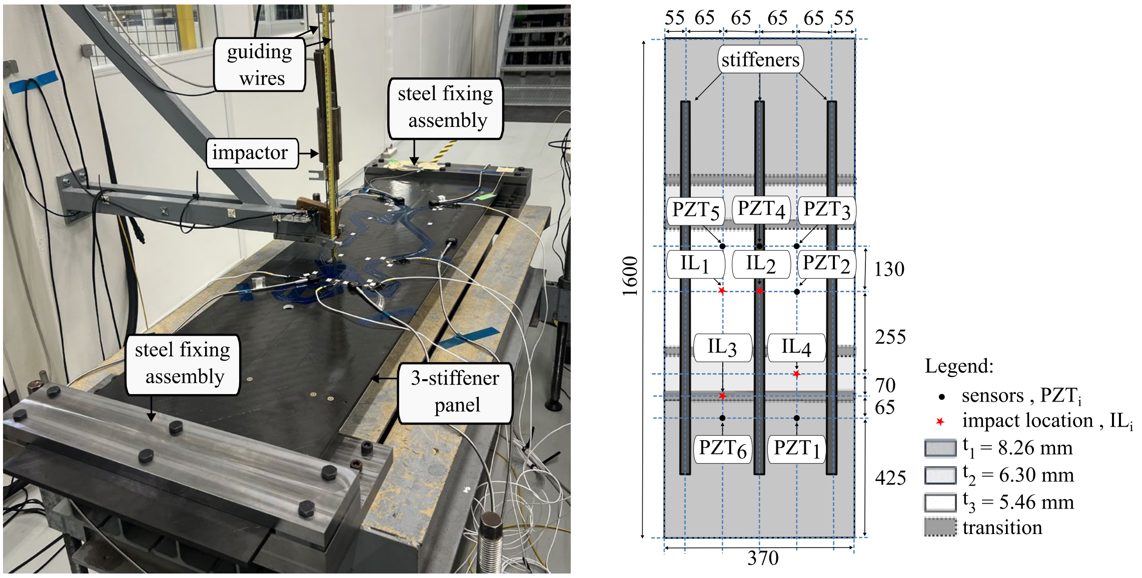
Several approaches have been proposed for impact identification based on sensor measurements. Examples of applications include methods based on data-driven approaches that rely on numerical simulation data, especially for coupon-level structures. For instance, Yu et al. [4] used a machine learning method to classify the impact energy in a flat composite plate. Similarly, Morse [5] proposed an artificial neural network for an impact categorisation algorithm. More recently, Yu et al. [6] introduced a strategy for impact identification using time reversal processing and numerical simulation data. In addition, Zhou [7] presented an innovative impact force identification method using regularisation strategies, which was validated by experiments on a square composite panel. However, the application to complex structures under more realistic conditions poses a significant challenge and is still very limited.

In response to this challenge, the present study focuses on impact categorisation to distinguish low-energy impacts from those that cause damage in a real-world composite structure using passive measurements obtained from PZT sensors. In particular, this work aims to comprehensively investigate the influence of structural complexities on sensor readings and evaluate the performance of signal features for impact categorisation at critical locations. In the end, this study contributes to ongoing research on impact identification by providing valuable insights into the effects of structural inhomogeneities on impact responses.

1 Experimental Set-up

Drop-weight intermediate-mass impact tests were performed from the outboard side using an impactor with a 16 mm head diameter and 2.356 kg mass. The test object was an AS4/PEEK thermoplastic composite structure with three stiffeners, a quasi-isostatic lay-up, and approximate dimensions of 1600 x 370 mm. The target structure is clamped on two of its edges using steel fixing assemblies, as shown in Fig. 1a. The thickness variation of the panel skin is indicated in Fig. 1b.

The test was carried out at four locations (IL*i* in Fig. 1b) with different impact energies ranging from 4.0 to 80.0 J. The experimental procedure started with low-impact energy and progressed to high-impact energy, resulting in internal damage. Phased array scan inspections were used for damage detection. Six piezoelectric P-876 DuraAct Patch Transducer sensors (PZT*i* in Fig. 1b) were installed to measure impact responses. The sensors were mounted opposite to the stiffeners. The measurements were processed using USB oscilloscope Handyscope HS6DIFF + HS5 at a sampling frequency of 1 MHz.



a. Test set-up. Stiffeners are located at the bottom of the panel.

b. Sensor network and impact locations. Not to scale. Dimensions in millimetres.

Fig. 1. Test configuration.

2 Results & Discussion

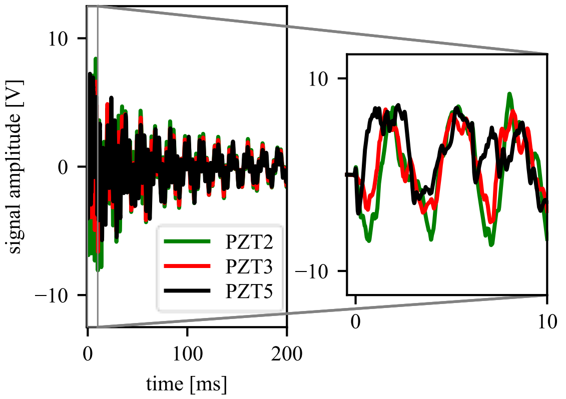
In this section, the impact experiment results are presented. Specifically, the impact responses are used to examine how structural elements, such as stiffeners and variable thickness, can influence the sensor data for impact detection in a realistic aircraft structure.

2.1 Time-domain comparison

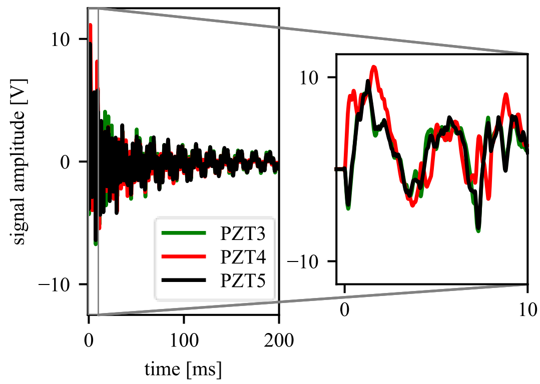
Here, 8J impacts and their interactions with structural features were analysed using different sensor positions. In particular, the waveforms of the impact on IL1 (as shown in Fig. 2a) measured by PZT2, PZT3 and PZT5 were analysed. It was observed that the waveforms of PZT2 and PZT3 were similar apart from the higher amplitudes of PZT2, which can be attributed to its shorter distance to the impact. However, differences were observed between PZT2/PZT3 and PZT5 due to different propagation paths. Notably, the presence of a stiffener affected the readings of the PZT2 and PZT3 sensors, while PZT5 received the signal with less interference. Similarly, the time signals caused by an impact on IL2 also showed high qualitative similarities between the sensors in the mid-bay (PZT3 and PZT5), as shown in Fig. 2b. In contrast, the measured response of the sensor located on the outboard side of the stiffener (PZT4) was not comparable to the other two.

In addition to the interference caused by the stiffeners, the influence of the variable thickness was also investigated. The results showed that the measurements of the sensors located in different thicknesses (PZT5 and PZT6) differed significantly upon impact at IL3

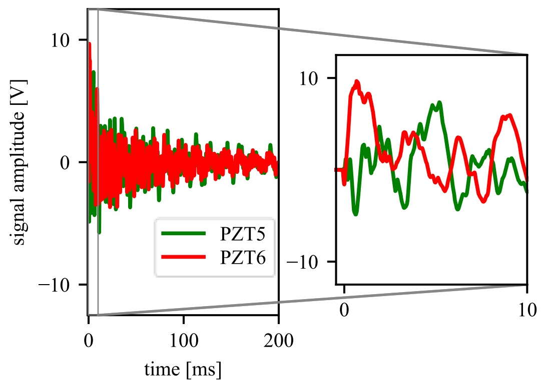
(Fig. 2c). Similarly, the readings of the sensors located at thickness t_3 (PZT2 and PZT3) were consistent on IL4. However, the waveform of the sensor at thickness t_1 (PZT1) differed from the others, as can be seen in Fig. 2d. These results confirm that the presence of structural inhomogeneities alters the wave propagation, which is caused by the physical principle of scattering due to the interaction of the waves with discontinuities [1,9].



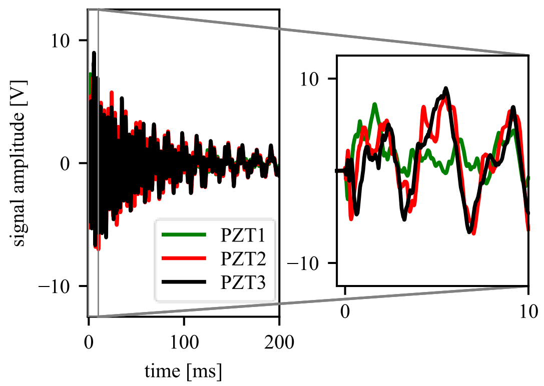
a. PZT2, PZT3 and PZT5 measurements due to an 8J impact at IL1.



b. PZT2, PZT3 and PZT5 measurements due to an 8J impact at IL2.



c. PZT5 and PZT6 measurements due to an 8J impact at IL3.



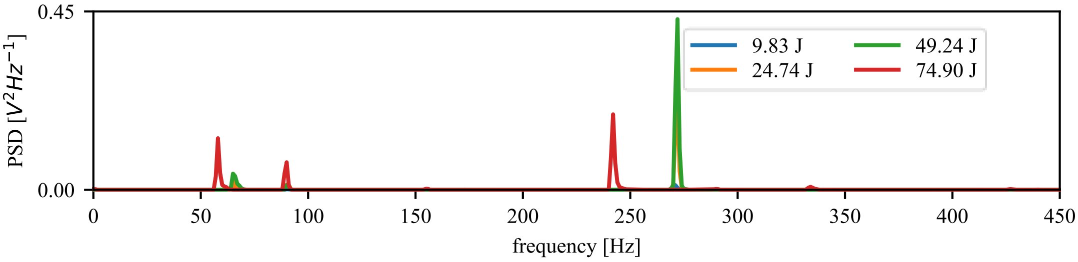
d. PZT1, PZT2 and PZT3 measurements due to an 8J impact at IL4.

Fig. 2. Time-domain impact responses.

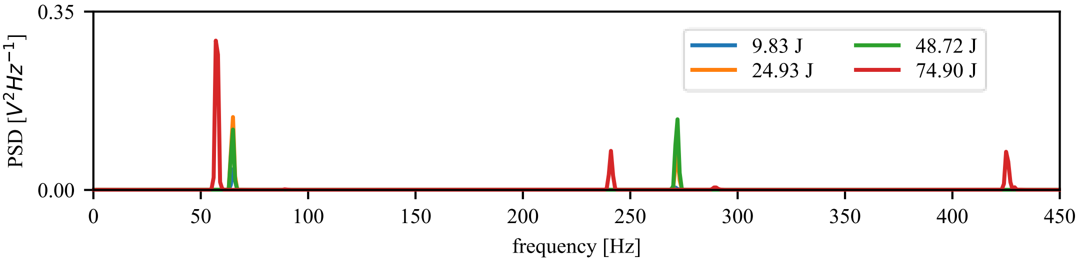
2.2 Frequency-domain comparison

Previous research has shown that analysing power spectral density (PSD) [10] can help classify impacts and determine the dynamic characteristics of the structure [11]. Furthermore, Olsson [12] indicates the predominance of the lowest vibrational modes on the dynamic behaviour of intermediate-mass impacts. Accordingly, a comparison of PSD plots at four locations (IL1-IL4) in the frequency range from 0 to 450 Hz with a frequency resolution of 1 Hz is presented. This approach aims to evaluate the energy distribution of the mode shapes and provide insight into the behaviour of a structure when exposed to different impact energies.

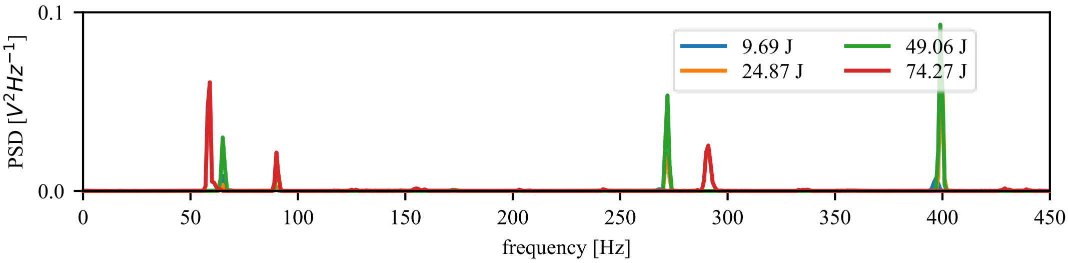
As shown in Fig. 3, the frequency components remain relatively consistent at lower energy levels (10, 25 and 50 J). However, the resulting spectrum distribution exhibits evidence of non-linearity at higher energy impacts (75 J) for all impact locations in the composite structure. In particular, an increase in external excitation leads to a shift in the frequency peaks or a significant reduction of dominant frequencies. This observation can be attributed to the non-linear material response of damaged composite structures. In this context, the dynamic behaviour and damage characteristics are further discussed in the following section to characterise the impact events.



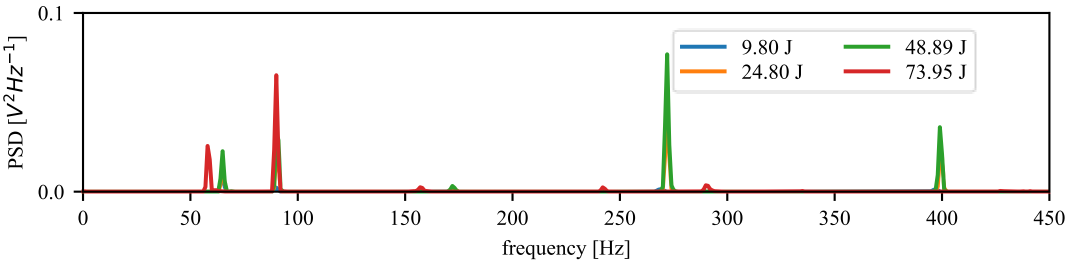
a. PZT5 spectral distributions due to impacts at IL1.



b. PZT2 spectral distributions due to impacts at IL2.



c. PZT6 spectral distributions due to impacts at IL3.



d. PZT1 spectral distributions due to impacts at IL4

Fig. 3. *PSD plots*

2.3 Impact Categorisation

Effective impact monitoring systems must distinguish between low-energy impacts and high-energy impacts that can cause damage. However, the system must consider factors beyond the energy level to classify an impact event accurately. For example, if the same impact energy is applied at different locations or with varying mass and velocity combinations, this can trigger different responses in the structural component. Table 1 provides an overview of the impact energy levels related to the damage onset, E_0, for all four impact locations (IL1-IL4). If the energy values are below the threshold, they are categorised as non-damaging, while values above are considered damaging impacts. Damaging impacts are labelled as BVID in the legends of the plots.

Further, to perform a comprehensive assessment of the damage and understand the behaviour of the structure during an impact, it is useful to calculate the absorbed energy for all impact locations before proceeding with the analysis of the signal features. This crucial impact parameter can indicate the occurrence of internal damage [13] and is determined by measurements from the instrumented drop tower. Fig. 4 shows a linear correlation between the impact energy and the absorbed energy at the impact locations IL1, IL3 and IL4, both in the pristine and the damaged states. However, the absorbed energy curve in IL2 behaves differently from the others. It shows a linear increase up to a threshold value of about 65J, beyond which a decrease in absorbed energy and a reasonable degree of non-linearity can be observed in the damaged state. The stiffener under IL2 can lead to different intralaminar damage due to impact loading and subsequently influence the absorbed energy.

Table 1. Damage at impact locations.

Impact Location	Characteristics	E_0, Damage Onset [J]
IL1	in the mid-bay, t_3	55
IL2	on the stringer	45
IL3	at the thickness transition, t_1 - t_2	55
IL4	in the mid-bay, t_2	50

To better understand how the structure responds to different geometries and structural inhomogeneities, signal features at critical impact locations (IL1-IL4) were analysed. This approach enables the evaluation of the effect of changing location on the performance of the signal features for impact categorisation. As previous sections have demonstrated, the impact response can vary depending on the position of the sensors relative to the impact source. Therefore, averaging the values across all sensors in the network may allow for more effective identifiers. The first feature examined was the transmitted energy, which is determined by the area under the squared magnitude of the time signal [14]. The second feature was the spectral energy, defined by integrating PSD over a frequency range [5].

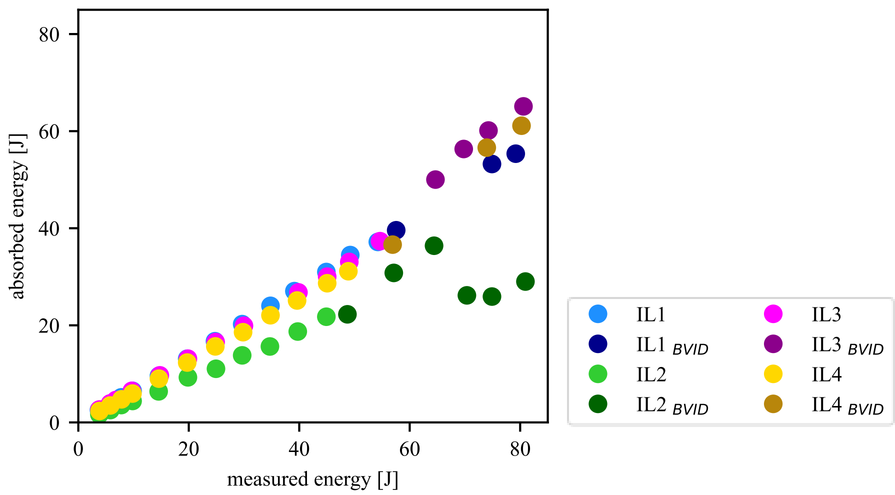
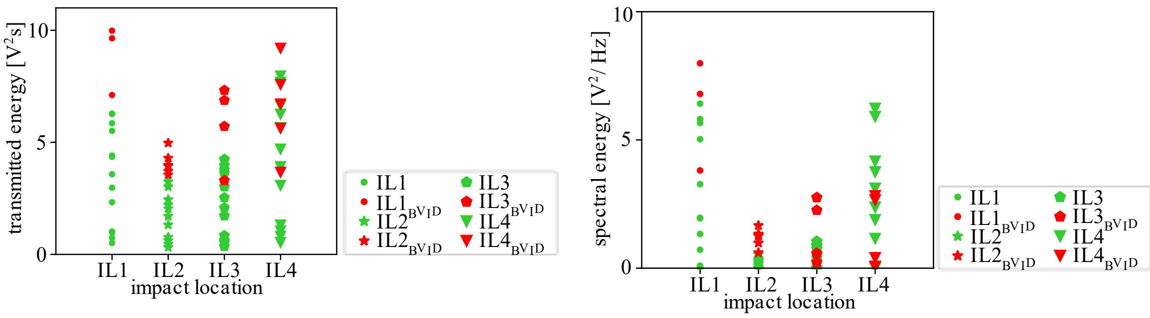


Fig. 4. Absorbed energy at impact locations for varying impact energy.

The analysis of the transmitted energy has shown the efficacy of the proposed feature in discerning between the pristine and damaged states in IL1 and IL2, as shown in Fig. 5a. It is noteworthy that a distinct value of the transmitted energy signal is linked to the onset of damage. However, for the thicker composite sections (IL3 and IL4), the categorisation method was unable to identify a clear threshold. This result is consistent with previous research that has reported the negative influence of increasing thickness on the effectiveness of damage detection, even with established NDI techniques [15,16]. Furthermore, the literature suggests that the initiation and formation of damage in thick composites differ from those in thin laminates [17], leading to variations in impact response features.

In contrast to the characteristics of the transmitted energy, Fig. 5b shows a low efficiency in categorising the impacts into spectral energy values, with the exception of the impacts at IL2. It is a challenge to distinguish between pristine and damaged states based on spectral energy values alone. The observed low spectral energy values can arise from either low energy impacts or reduced amplitudes in the natural frequencies due to damage [11]. Thus, the low spectral energy values remain ambiguous. This observation underlines the need for a more comprehensive approach to categorising impacts into damaging and non-damaging that takes into account not only spectral energy values but also other factors.



a. Average transmitted energy at impact locations. b. Average spectral energy at impact locations.

Fig. 5. Signal features for impact categorisation.

3 Conclusions

In this study, the impact characterisation of a stiffened composite panel using passive sensing systems was investigated. The experimental results showed that the presence of structural inhomogeneities significantly affects strain wave propagation and the associated sensor readings. The low-spectral frequency content of the impact signals was found to be consistent at all impact locations, but the amplitude of the dominant frequency varied depending on the sensor location. In addition, a categorisation method to distinguish between damaging and non-damaging impacts was applied. The results showed low efficiency in categorising impacts into spectral energy values and highlighted the effect of increasing thickness on the effectiveness of damage detection. Finally, this work emphasises the importance of integrating structural features into impact identification methodology to achieve efficient SHM under practical applications.

4 Acknowledgement

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