Enabling Distributed, Multifunctional SHM Through Integrated Metamaterials and Piezoelectrics

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ABSTRACT

Structural Health Monitoring (SHM) is essential for ensuring the safety and longevity of critical infrastructure. Traditional methods face limitations in spatial coverage, susceptibility to environmental factors, and complex data interpretation. To address these challenges, this research proposes an intersection of mechanical metamaterials with embedded piezoelectric sensors. Metamaterials enable distributed sensing while maintaining the load-bearing capacity of a structure. Piezoelectric materials provide passive strain/vibration sensing and vibration-damping capabilities. Integrating piezoelectric elements with a tailored re-entrant mechanical metamaterial design enables smart support system beam condition monitoring. Experimental validation was conducted on an aluminium beam supported by a pin and roller supports, exploring the feasibility and potential of this smart SHM system. This approach offers distributed sensing, multi-functionality, and more resilient built environments that continuously monitor their structural health and adapt as needed. This paper demonstrates the potential of a smart engineering support system for SHM.

INTRODUCTION

Research into Mechanical Materials (MM) in engineering is advancing as their applications expand across various domains. The artificial design of these materials' mechanical properties and unique functionalities render them attractive for active metamaterial research, thereby enhancing structural performance [1], [2]. Smart structures provide a viable solution by incorporating distributed actuators and sensors, alongside one or more control units for in-situ monitoring. This approach enables the development of a new generation of structures with integrated sensing and actuation capabilities designed from their inception [3], [4]. The ongoing exploration of these two areas promises to yield next-generation materials and structures capable of autonomous operation and enhanced performance in various engineering challenges.

When analysing changes in the structure's condition, a set of non-destructive testing

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(NDT) methods is usually employed, such as acoustic emission [5], electro-mechanical impedance [6], eddy currents [7], and thermography [8]. NDT tests are typically performed at regular intervals; However, this approach does not eliminate the risk of failures occurring between inspections. To combat this limitation, continuous monitoring is sought to acquire data on the structure's condition during its lifetime. This has led to research interest in embedded sensors (ES), for SHM applications, where sensors can provide real-time information throughout the structure's life cycle [9], [10], [11].

This intersection between sensors, smart materials and structures, mechanical metamaterials, and the goal of smart structures creates an opportunity to embed sensors and actuators into structures with the aim of self-sensing, self-actuating structures that can self-evaluate and prompt assessment of their condition [12], [13].

An important part of SHM involves identifying impact load locations and amplitudes for damage assessment. Impact load monitoring typically uses two approaches: a model-based and a data-driven approach. The model-based approach, often in the frequency domain, relies on linearised models derived from matrix inversion based on known mechanical excitation and structural response. This is suitable for stationary conditions but faces challenges. In the time domain, motion equations are used with the Green kernel function method or recursive expressions for non-stationary processes [14]. The data-driven approach uses measured structural responses and known excitations to develop statistical models. While advantageous for complex nonlinear systems, obtaining sufficient measurement data can be difficult, affecting model performance [15].

In this work, a smart engineering support was designed to integrate a smart piezoelectric material, inspired by an artificially designed structure based on re-entrant MM geometry. Piezoceramic was embedded in a mechanical pin and roller support laboratory sample to detect the mechanical responses of an aluminium beam while maintaining sufficient stiffness to resemble an actual engineering support. This setup was used to evaluate the viability of this smart support concept for vibration assessment and possible load monitoring by comparing its performance on a healthy beam and a damaged beam with a distributed support system.

MATERIALS AND METHODS

The concept of integrating a smart piezoceramic material in the structure is represented in the Figure 1 (left), showing the concept of smart support, where a smart self-sensing material is integrated into the support structure connected to the host support. Enough stiffness is required to withstand the load of the supporting structure and the ability to transmit the vibration from elastic waves coming from the dynamic response of the supported structure or the load on the support itself, allowing continuous monitoring of the support and the structure. The sensing element in the support is bonded to the immovable part of the support on one side and the other with a stiff connection to transfer small vibrations to the sensing element. The stiffening effect of the Lead Zirconite Titanite (PZT) element was tested using a static material testing machine EA05 from STEP Lab Corp..

A re-entrant mechanical metamaterial was chosen as a basis for a smart support concept suitable for supporting an aluminium beam. A pin (79.4 g) and roller (80.6 g) support was selected as a test subject. A steel pin connects the aluminium rod (156.7 g)

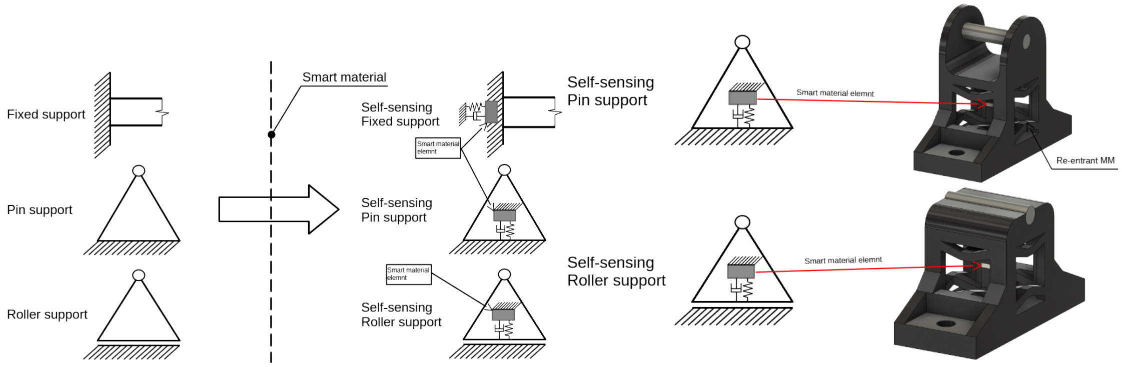

Figure 1. (left) Flow chart for smart engineering supports and (right) Pin support and roller support models for a beam with integrated PZT elements.

to the pin support. The support is manufactured with the use of Fused Deposition Modelling (FDM) with 95%+ infill and an integrated PZT PIC255 element with dimensions of 5x5x0.5mm (Figure 1 right). The PZT is sandwiched between two metal electrodes and a pair of wires. The aluminium beam in Figure 2 (left) is divided into five segments with six impact locations. Two laboratory configurations were used: a pin and a roller support below the locations L_0 and L_3. And the second configuration with pin and roller supports below L_0, L_2 and L_4, respectively. The aluminium beam was subjected to impacts with measured loading, and elastic vibration measurements were acquired through the smart supports (Figure 2 left). A healthy beam with and without added weight (60 g), with two support configurations, and a damaged beam with a saw dent (3x3x5 mm) and an added weight were created for both testing scenarios. The distances are $a = 7.5cm$, $b = 7cm$, $c = 5cm$, and $d = 3.5cm$.

The experimental setup is depicted in Figure 2, where an impact hammer 086c03 from PCB electronics with a white vinyl tip and a blue cap was used to excite the beam and acquire the excitation signal. The response of the aluminium beam was measured with the pin and roller supports. The measurement system comprises an NI-cDAQ-9174 with two NI cards 9234 and 9239, a sampling frequency of 25600 Hz and a pre-trigger of 0.01 s. Fifteen or more measurement repetitions at each impact location L_i, where $i \in \{0, 1, 2, 3, 4\}$, were performed in two support configurations with three and two self-sensing supports; the double impacts were discarded. The healthy beam was measured with and without added mass at the location L_5 and with distributed sensing configurations. The damaged beam with a dent was measured with and without added mass in the two configurations.

An impact excitation-response measurement was performed for each support. To analyse the feasibility of SHM and dynamic loading sensing for identification, a cross-correlation (Equation 1, from scipy.signal python library) method is used. Measurements were normalised with min-max feature scaling. Measurements that were not discarded in the initial preprocessing stage due to double impacts were used further. The normalised signals were correlated between healthy and unhealthy states for each sensor. For statistical evaluation of measured data, a T-test with a 95% confidence level was used with samples n=7 and n=11 for three support and two support configurations, respectively. The cross-correlation was performed between the healthy state, the weight-loaded state,

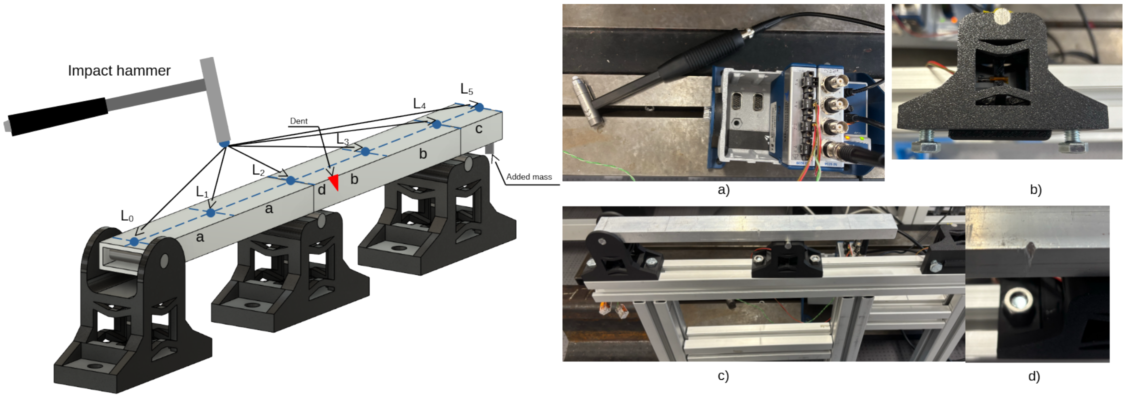

Figure 2. (left) An assembly of aluminium beams and smart supports with given impact locations, dimensions and highlighted damages. (right) Experimental setup: a) Impact hammer 086C03 and NI-cDAQ-9174 with two NI cards: NI-9234 and NI-9239, b) close-up on a laboratory sample of a roller support, c) experimental setup with aluminium rod and d) close-up to a dent in an aluminium beam.

and the damaged scenarios. In the case of configuration two with only two supports, a cross-correlation was performed against the signal from the healthy scenario of the sensor closest to the damage and added weight. In the first scenario, the signals of healthy and unhealthy states were compared to the particular sensor signal only.

$$z[k] = (x * y)(k - N + 1) = \sum_{l=0}^{||x||-1} x_l y^*_{l-k+N-1} \tag{1}$$

RESULTS AND DISCUSSION

To observe a stiffening effect within the smart support, a compression test with a displacement load of 1 mm was performed for the roller and pin support, and the resulting stiffness is shown in Table I.

The frequency range of impact hammer excitation was not greater than 300 Hz above 3 dB, the only excitable mode within the frequency range of the aluminium bar was around 250 Hz, and thus the amplitude of the response signal decays relatively rapidly, as shown in Figure 3. The graphs for different impact locations and the same support one reflect the impact lag against the distance from the impact, and the various damage configurations also show differences. To see the feasibility of the support distribution and the ability to identify the differences in healthy and unhealthy scenarios, the cross-correlation results are presented in Figures 4 and 5. Configuration 1 demonstrates the possibility of finding the unhealthy beam or changes in the beam's condition. However, configuration 2, with only two supports, shows better capability for impact location identification and SHM.

The last graph in Figure 3 shows an unintended effect of the nonideal mechanical assembly of the beam and smart supports. The not-ideal straightness of the bar and imperfections in the pin joint show not-ideal vibrations because of the lack of ideal

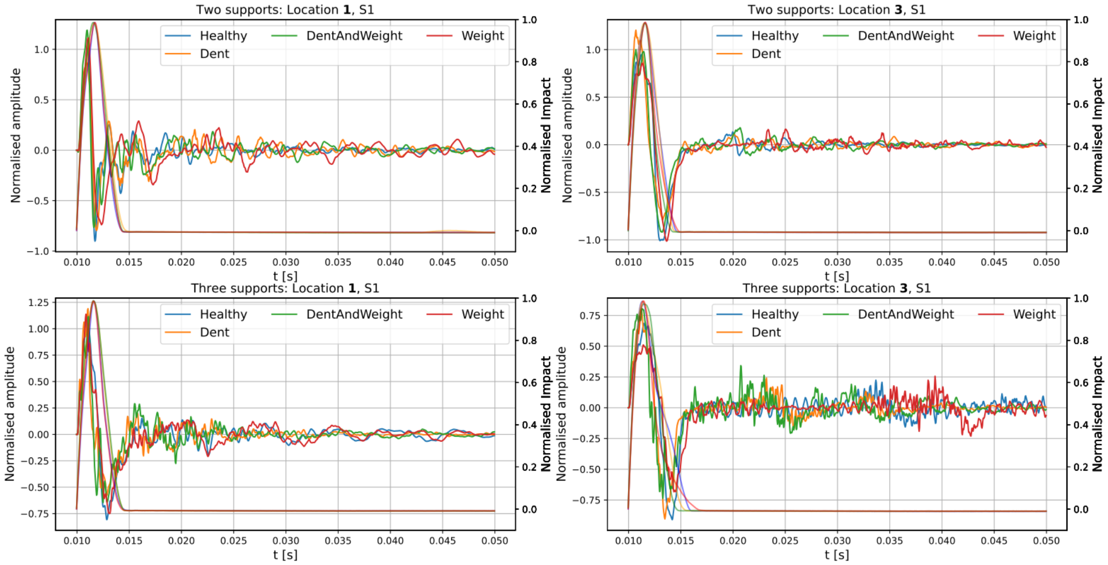

Figure 3. Post-processed impact-response for configurations one and two for locations L_1 and L_3 for healthy and damaged structures.

alignment of the laboratory specimen, and thus, insufficient contact between supports one and two. In addition to the ringing and varied response, a cross-correlation (Figure 4) still detects the differences between a healthy and unhealthy aluminium beam. On the other hand, Figure 5 shows that the configuration with only two supports does not have this problem, and shows better that the support is closer to the added mass and damage. It also shows that as the distance to the impact location from the dent and the added mass closes, a distinction can be made between the position of the beam damage and the impact location and the support location. The confidence intervals for the T-test show statistical significance that the unhealthy state differs from the healthy one, and also highlight the mechanical impairment in the three-support scenario, where the last support is not perfectly aligned with the second one. Thus, the statistical significance of the unhealthy scenario is diminished. The three support configurations (Figure 4) show statistical significance in the impact of unhealthy state on the sensor **S0** and **S1** between the location **0** and **1**, due to uneven support **S1** and **S2**; however, in all impact locations **0-5**, a **S1** support shows consistent results. However, the two support configurations imply the noticeable effect of weight, dent and their combination on the signal. Only when the impact location reaches the support location **3**, and further. The significance of the **S0** output signal is less correlated with the support **S1**.

TABLE I. Stifness comparison between pin and roller supports fabricated through FDM and assembled with and without PZT element.

	Pin [N/mm]	Roller 1 [N/mm]	Roller 2 [N/mm]
PZT	1360	2862	1628
No PZT	796	1188	1147

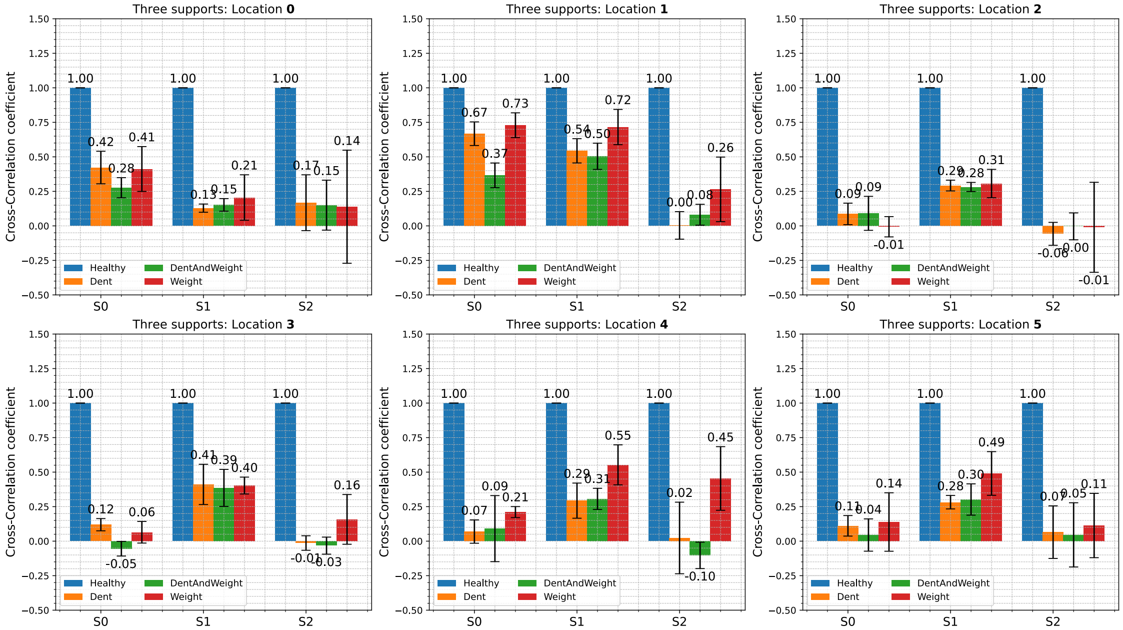

Figure 4. Healthy vs. unhealthy beam: Cross-correlation coefficient normalised against each Support’s healthy amplitude for all six locations L_i.

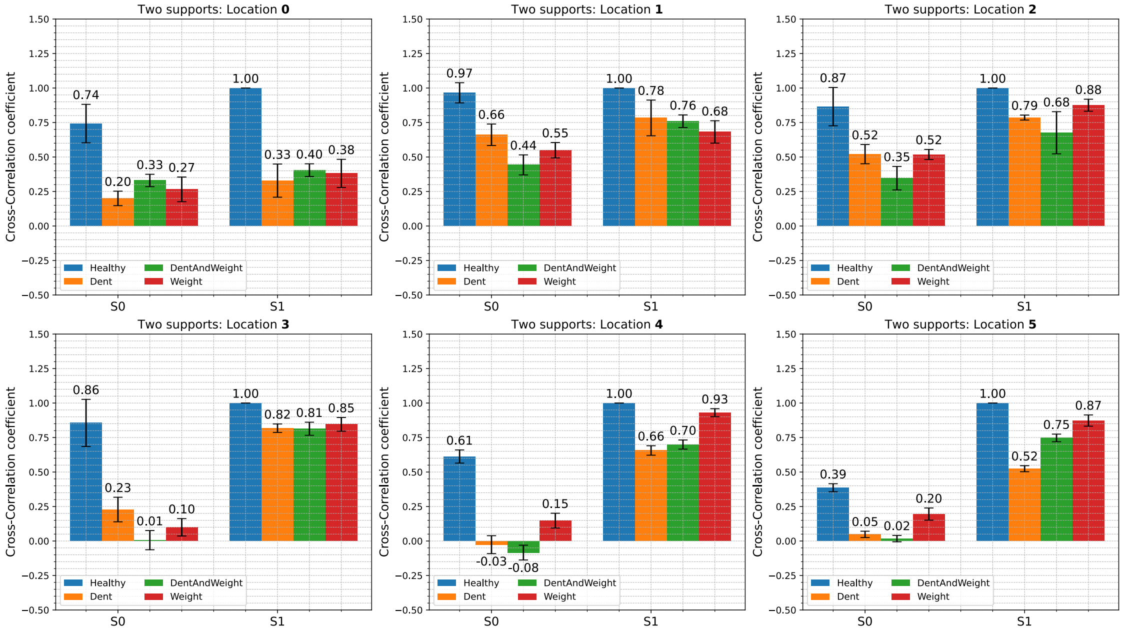

Figure 5. Healthy vs. unhealthy beam: Cross-correlation coefficient normalised against the Support 1 healthy amplitude for all six locations L_i.

CONCLUSION

This study investigated the viability of integrated piezoelectric elements with a tailored re-entrant mechanical metamaterial design to create a smart support system for beam SHM. Our findings show the successful use of the smart support design and its ability to monitor condition differences due to damage or added weight. The results show potential usability for monitoring the condition of a host structure with a smart support system. Further research will focus on the impact of load identification and location prediction. A similar support system for a plate-like structure will also be used to test the potential use of the support.

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DATA AVAILABILITY STATEMENT

The data supporting this study’s findings are openly available in the Zenodo repository at https://doi.org/10.5281/zenodo.15301836.

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