MATERIAL SELECTION FOR FUNCTIONALIZED FIBER-REINFORCED COMPOSITE STRUCTURES

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ABSTRACT

The selection of appropriate materials for functionalized structures poses a significant challenge, given the vast number of fiber-reinforced composite materials available for host structures and the wide variety of piezoelectric materials to choose from. This study selected PVDF, a polymer-based piezoelectric material, as the active element and pre-impregnated unidirectional flax fiber as the base material for the creation of new aeronautical structures capable of detecting and monitoring fractures. Flax fibers were qualified for the study based on their promising electrical resistance and insulation properties, as determined by classical continuity and impedance tests performed on the sample prepared with connectors embedded in Carbon and Flax fiber prepreg structures. On the other hand, the choice of piezo as an embed was primarily inspired by its measurement capabilities. A polymer-based piezoelectric material was considered for its flexibility compared to ceramic and single-crystal counterparts, as it offers both adaptability and acceptable environmental friendliness. Finally, we realized laminated composites with a symmetrical lamination scheme $[0°/90°/0°]_s$ from the selected materials and performed vibration tests with magnetic manipulation to investigate the functional properties of the resulting smart materials.

1 INTRODUCTION

The development of advanced composite materials with enhanced performance continues to receive significant attention from researchers. The constituent materials play a crucial role in the composite structure's optimal performance and dependability, necessitating careful selection to ensure compatibility. This work focuses on material selection used in composite structures and active materials, particularly piezoelectric materials, for potential integration during the design and manufacturing phases. We propose to embed piezo-based sensors into a composite material structure during fabrication instead of attaching external sensors. Incorporating active elements in traditional composite materials produces new innovative composite structures [1]. When applied in the aerospace industry, such materials can detect cracks sustained from the design and fabrication process and defect occurrences during typical operations, thus enhancing structural health monitoring [2, 3].

This material selection process is a crucial step in designing and producing smart composite structures that utilize piezoelectric and fiber-reinforced composite materials. The choice of materials directly impacts the performance and functionality of the final composite structure [4]. For piezoelectric materials, considerations such as piezoelectric coefficients, mechanical properties, temperature stability (Curie temperature), and environmental impact are important factors to be considered. The selection of appropriate piezoelectric materials is essential to ensure efficient energy harvesting, sensing, or actuation capabilities in the smart composite structure [5].

Similarly, for fiber-reinforced composites, properties such as fiber type, orientation, volume fraction, matrix material, and manufacturing process significantly affect the composite structure's mechanical, thermal, and electrical properties [6]. It is, therefore, imperative to pick a combination that will improve performance and preserve the ideal physical, mechanical, and chemical qualities of the respective constituent materials.

The present study involved a meticulous selection of materials for developing a smart material structure, focusing on their intended functionality. The primary factors considered encompassed the capacity of the host fiber-reinforced composite material to provide adequate insulation for the embedded sensor, the curing temperature, ensuring that it remained below the Curie temperature of the chosen piezoelectric material, and the production process of the smart composite. These criteria were of utmost importance in ensuring the feasibility and viability of the resulting smart material structure for future deployment in aerospace applications. Furthermore, the high preference for eco-friendly materials and the strict environmental controls put into place are also factored into the primary considerations when choosing materials [7]. Thanks to the development of natural fibers for technical applications and the accessibility of eco-friendly piezoelectric materials [8, 9]. Moreover, the material selection process should also consider the lifecycle performance and sustainability aspects of the smart composite structure. Environmental considerations such as recyclability, energy consumption during manufacturing, and end-of-life disposal should be considered. Additionally, the long-term durability and reliability of the selected materials in the operational environment of the smart composite structure, including temperature, humidity, and mechanical loading conditions, should be evaluated. It is, therefore, essential to note that proper material selection can contribute to the smart composite structure's overall sustainability and lifecycle performance, ensuring its functionality and durability throughout its service life.

Moreover, the selection of manufacturing procedures and processes is intricately linked to the choice of materials. Numerous research papers in the existing literature have proposed various methods for fabricating smart composite materials [10 -13]. These approaches encompass the direct embedding of piezo material between two plies [14], the strategic removal of fibers in the active element's location to match the structure's thickness [15], and the appropriate wire-out techniques [16]. It is also worth noting that when the embedded element is placed directly between plies, the continuity of the plies and fibers is preserved. However, when fibers are cut out, there are discontinuities at the fiber layers due to the cutting required to accommodate the inserts [17-19]. This raises concern as the mechanical strength of the composite structure is sought to ensure that it can withstand stress/strain impacts within its operating environment without failing. Contrary to the cut component, continuous fibers, in this case, produce quality reinforcing strength. However, this may also introduce unwanted thickness variation exceeding the allowable limits in the final products. In order to overcome these constraints, the present work will seek to choose materials that minimize the detrimental effects of inserts on the structural integrity and physical conformity of the structure while ensuring desired functional characteristics.

Based on a systematic approach that included a comprehensive literature review and experimentation to select the most suitable materials for the intended application. Considering various factors such as functional requirements, manufacturing constraints, and lifecycle performance, flax fiber and PVDF (Polyvinylidene fluoride) was chosen as the optimal materials. The selection of flax fiber and PVDF piezoelectric material for producing smart composite materials holds promising potential for various applications, including sensing and energy harvesting. Flax fiber is an attractive alternative to carbon or glass fibers thanks to its inherent sustainability, low environmental impact, good electrical insulation properties, and excellent mechanical properties, such as a high strength-to-weight ratio and good damping characteristics. In piezoelectric materials, PVDF emerges as a favorable choice over materials like PZT (Lead Zirconate Titanate) due to its flexibility, elasticity, and resistance to brittleness under mechanical stress [20].

Furthermore, PVDF offers the advantage of being non-toxic, alleviating concerns associated with the presence of lead in PZT, and ensuring the safety and environmental friendliness of the composite material. By combining the mechanical properties of flax fiber with the flexibility and non-toxic nature of PVDF, the resulting smart composites achieve an optimal balance between structural functionality, performance, and environmental sustainability, making them highly suitable for sensing, actuation, self-sensing and energy harvesting applications [20 - 26].

The utilization and practicality of flax fiber-reinforced composites have garnered significant interest as an alternative to synthetic materials within the aviation and transportation industries. While carbon fiber reinforced polymers (CFRP) have been extensively employed due to their exceptional mechanical properties, their energy-intensive production necessitates the exploration of bio-based alternatives. Flax fibers possess cost-effectiveness and widespread availability, rendering them highly appealing for industrial applications [27]. By reducing reliance on energy-intensive materials and promoting sustainability, flax fiber composites have the potential to impact modern aircraft and transportation systems substantially. Their use is primarily limited to secondary parts, while their utilization in primary load-bearing components remains constrained [28]. Nonetheless, certain research studies have highlighted their suitability for hybrid composite development, particularly in combination with carbon fibers [29]. This approach proves advantageous in manufacturing smart composite materials, as flax fibers can provide desired electrical insulation for sensors while carbon fibers contribute significant mechanical strength.

Additionally, proper material selection plays a pivotal role in addressing the need to monitor operating structures' integrity, especially as sustainable materials gain momentum and seek to enhance natural fibers in technical applications. While composites offer attractive properties like lightweight construction, making them highly appealing to aerospace industries, their true potential is hindered by the inherent variability and complexity of failures they may encounter. Matrix cracking, fiber failure, debonding, and delamination are common issues that can lead to catastrophic failure if not promptly detected and analyzed [21]. To tackle these challenges, researchers are actively exploring the implementation of embedded sensors, with a specific focus on piezoelectric materials, to develop structural health monitoring techniques. By integrating these sensors directly into the composite, the reliance on external components is eliminated [21]. Notably, PVDF has demonstrated exceptional capabilities in sensing and energy harvesting applications, making it an optimal choice for achieving the desired functionalities.

In this study, we selected PVDF, a polymer-based piezoelectric material, and pre-impregnated unidirectional flax fiber. Laminated composite samples were fabricated using a symmetrical lamination scheme $[0/90/0]_s$, with PVDF embedded in different layer positions for each sample. Vibration tests with magnetic manipulation were conducted on the developed smart composite materials to explore their functional properties and sensitivity. Additionally, the electrical insulation properties of the fiber-reinforced materials were investigated during the material selection phase.

2 MATERIALS AND METHODS

The materials employed in this study encompassed flax fiber prepregs, carbon fiber prepregs, mu-copper tape, bronze wire mesh, aluminum foil, and polyvinylidene fluoride (PVDF), serving as the active element. The experimental samples were created utilizing the consolidation fabrication method (Fig. 2). This method involves applying pressure and heat to a pre-impregnated resin/fiber assembly to ensure complete infiltration and removal of trapped air and volatiles generated by the polymer during the heating phases. The resulting smart composite samples were rectangular, measuring 50mm by 92mm, with an embedded PVDF piezo film measuring 12mm by 52mm, oriented at 45˚. The piezo patch was positioned directly between the plies, and its thickness (0.052mm) had minimal influence on the overall thickness of the fabricated sample. Specifically, the piezo layer was located at the midplane of the composite (Fig. 1a), between layers 4-5 (Fig. 1b), and between layers 5-6 (Fig. 1c).

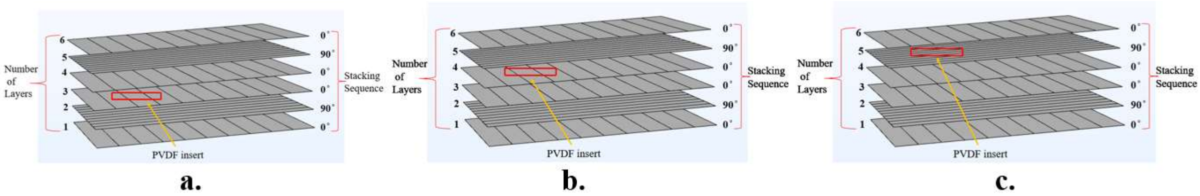
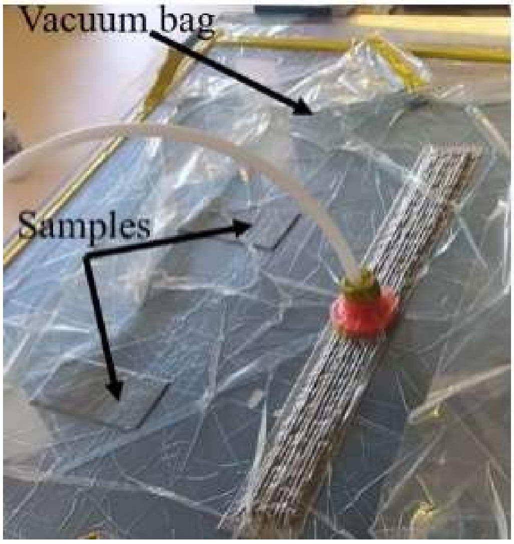


Fig. 1. Fiber orientation and embedded piezoelectric material position in the laminated smart composite structure.



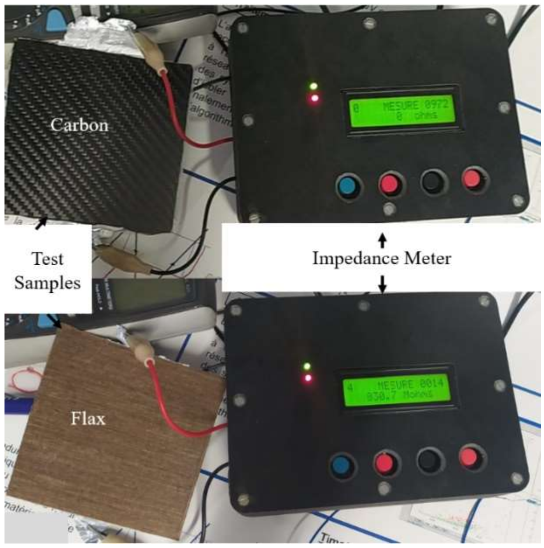


Fig. 2. Samples fabrication based on consolidation molding process.

Fig. 3. Samples conductivity test.

On the carbon and flax fiber samples explicitly fabricated for evaluation of the electrical conductivity and insulation property (Fig. 3), continuity tests and resistance measurements were performed. The actual smart composite samples were then subjected to vibration tests with sinusoidal electromagnetic excitations following the set-up shown in figure 4. The developed smart composite beams were clamped, and excitation of constant strength with varying frequencies was implemented to check on the response and sensitivity of the PVDF at different layers.

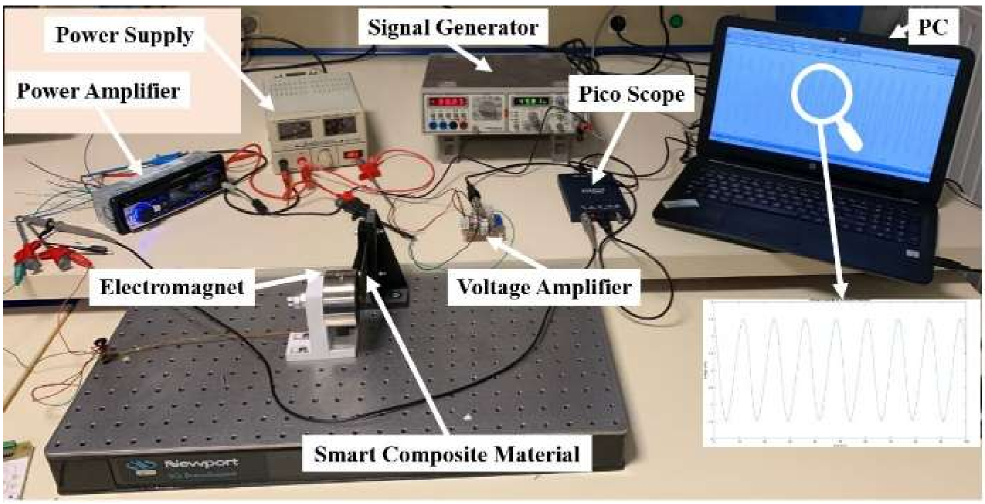


Fig. 4. Experimental setup for dynamic excitation tests.

3 RESULTS AND DISCUSSIONS

The environmental aspect helped to narrow down the material selection. Other technical considerations regarding the end product, particularly the thickness variation and sensitivity of the smart composite structure, have also been beneficial. Another important consideration was the non-planar nature of aerospace structures, which necessitated flexible, easy-to-fabricate, and customizable materials. These factors ultimately led to choosing a polymer-based piezoelectric material, specifically PVDF. The continuity test on the new materials revealed that the carbon fiber-based samples had low electrical resistance and thus poor insulation compared to the Flax fiber pre-impregnated ones (Table 1). This provided valuable insight into the feasibility of using flax fiber to prevent short-circuiting of the embedded sensor.

Composite's Fiber Type	Electrical Continuity	Resistance
Carbon	Yes	0 Ω
Flax	No	830.7 MΩ

Table 1: Electrical conductivity test results.

Composite Number	Number of Layers Stacking sequence $[0/90/0]_s$	Position of Piezo Layer	Pk-Pk Voltage (mV)	RMS Voltage (mV)	Resonance Frequency (Hz)
Sample 1	6	Layers 3-4	108.93	34.67	41.21
Sample 2	6	Layers 4-5	770.30	261.6	42.15
Sample 3	6	Layers 5-6	3017.60	1048	40.60

Table 2: The sensitivity test results from dynamic loading of the smart composite laminates. The peak to peak and the true RMS voltages were measured at resonance.

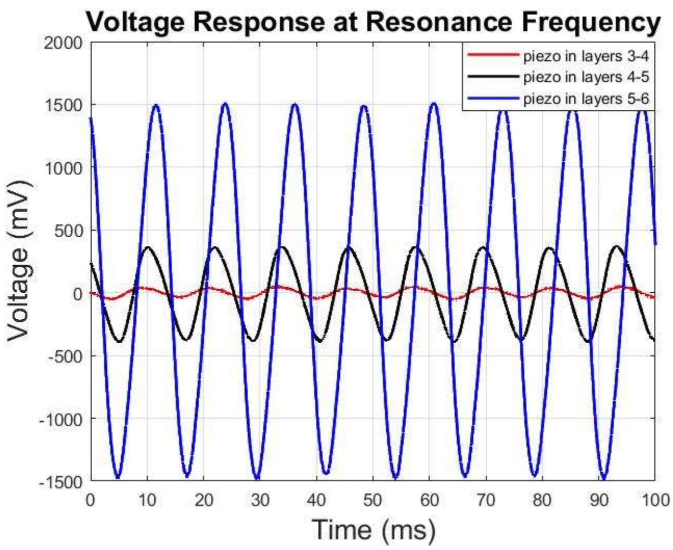


Fig. 5. Voltage response for the test samples with PVDF placed in different laminate layers.

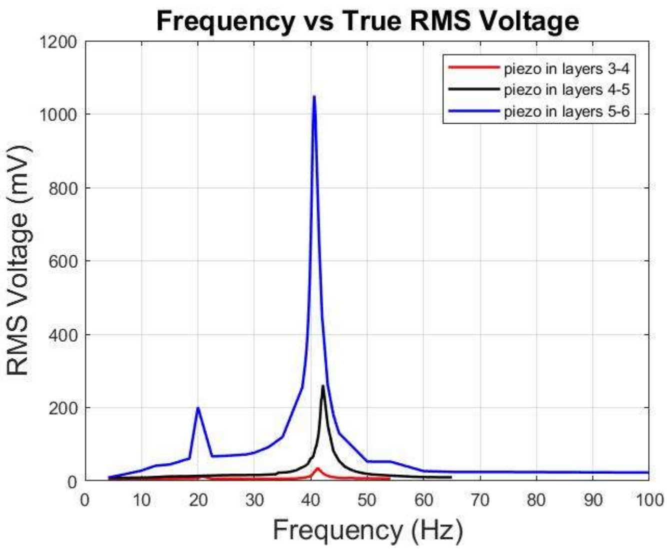


Fig. 6. Frequency response for the test samples with PVDF placed in different laminate layers.

Within the framework of sensitivity analysis, three distinct samples were examined. The first sample involved a PVDF piezo patch embedded in the midplane of the laminate structure. The second sample featured a piezo patch between layers 4 and 5, while the third sample had a piezo patch between layers 5 and 6 of the smart composite beam. All three pieces were subjected to dynamic bending induced by magnetic excitation. This investigation aimed to evaluate the impact of inter-lamina stresses on the piezo patches and assess their feasibility for practical sensing applications. The voltage responses were recorded using a PicoScope 2000 series and presented graphically in figure 5. Furthermore, the voltage responses at various frequencies were analyzed, resulting in identifying resonance frequencies plotted in figure 6. The obtained results were compiled and presented in Table 2.

From the results (Fig. 5), the voltage response of the smart composite structure with the sensor embedded in the midplane exhibits a small peak-to-peak voltage. This can be attributed to the unique stresses experienced by the midplane of the laminate during dynamic bending. As the beam bends, the midplane undergoes both tensile and compressive stresses. At the neutral axis, where the bending moment is zero, the midplane experiences minimal stress, resulting in relatively small strains approaching zero. This explains the observed signal to a large extent.

Furthermore, the presence of the piezo layer in the midplane slightly shifts the neutral axis, which can influence changes in stresses and strain distribution. Additionally, imperfections such as voids and resin pockets may cause non-linear stress distribution, leading to deformation of the PVDF piezo layer in this position. It is important to note that the stresses and strains experienced in this laminate region during dynamic bending through thickness are critical factors in determining the structural behavior and integrity of the composite laminate beam. Accurate analysis and understanding of these stress and strain distributions provide valuable insights for designing resilient and reliable composite structures capable of withstanding the demands of dynamic bending loads.

Nevertheless, strains progressively increase towards the outer layers, reaching their maximum magnitudes. This observation aligns with the voltage response evolution concerning the sensor's positioning in our test samples, as presented in Table 2. Based on these findings, it can be inferred that incorporating PVDF within electrically insulating bio-composite material retains its remarkable sensitivity. Thus, it holds promising potential for critical applications, including non-destructive health monitoring strategies currently under investigation within the aerospace industry.

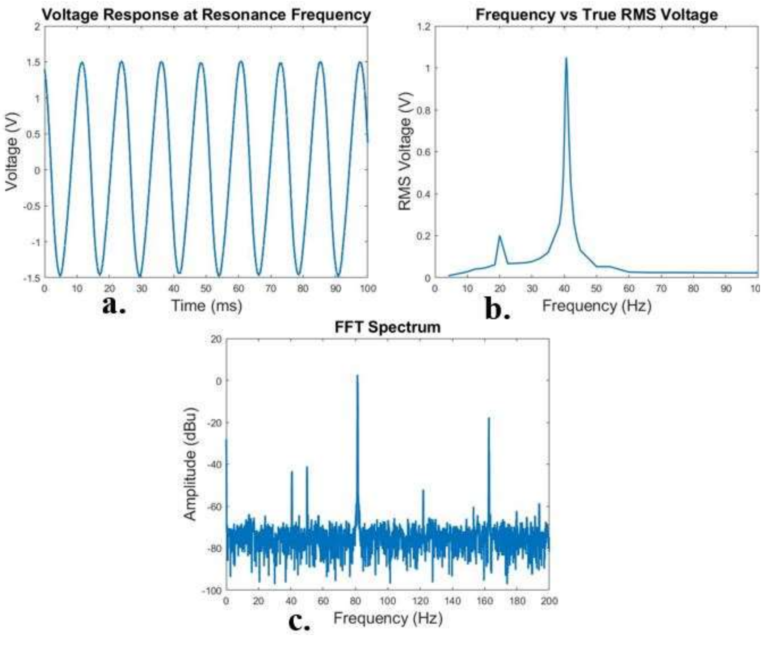


Fig. 7. Experimental results: a.) Voltage response from the excited sample, b.) Output rms voltage at varying frequencies, c.) Fast Fourier transform plot.

Figure 7 depicts the results of the dynamic vibration test performed on the structures. The sample of interest was obtained from examining the data in Table 2 to evaluate the energy harvesting capabilities of PVDF. Since this material can generate an electrical charge in response to mechanical strain, integrating it into sensor nodes placed on structures can convert the mechanical vibrations or deformations experienced by the structures into electrical energy. This energy can then be harvested and utilized to power the sensor nodes, eliminating the need for external power sources or frequent battery replacements. Their use in energy harvesting in structural health monitoring enables self-powered and autonomous monitoring systems and contributes to sustainability and cost-effectiveness. Thus, the combination of PVDF's energy harvesting capabilities with its sensing capabilities makes it a promising material for enhancing the efficiency and functionality of structural health monitoring sensor nodes. The resonance frequency was identified as 40.60 Hz (Fig. 7b). As shown in figure 7a, the peak-to-peak voltage at resonance frequency was approximately 3V, which is significant in the interest energy scavenging. Finally, we plotted the response's FFT spectrum (Fig. 7c). This aided n extracting the characteristic frequencies of our structure.

4 CONCLUSIONS

In the context of smart composite structures, the selection of appropriate constituent materials plays a critical role. For instance, precise dimensional control necessitates the use of relatively thin inserts compared to the ply thickness. Based on our observations, the utilization of PVDF has proven to be highly beneficial, effectively reducing thickness variation and preventing fiber cutting. Furthermore, dynamic vibration tests have confirmed the feasibility of implementing PVDF in aeronautical structures, considering the natural frequency range, voltage response, and the material's sensitivity. This establishes its reliability for applications requiring embedded sensors. Moving forward, our future work aims to explore diverse fabrication methodologies that align with the selected materials and investigate the signal response of various piezoelectric sensor placement configurations. Additionally, we will delve into advanced finite element analysis to validate the impact of interlaminar stresses as discussed in the results section.

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