Effect of Different Support Materials of Smart Sensor Layers on Lamb Waves Propagation

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Abstract: The present work aims to study the suitability of polyethylene terephthalate foil (PET foil), thermoplastic polyurethane foil (TPU foil), and Polypropylene (PP) laminated nonwoven fabric as support materials for PZT-based flexible sensors for SHM applications. Specifically, the aim is to find the effect of these materials on ultrasonic-guided wave propagation in composite structures. Kapton is also used as a support material for comparison. Experimental studies are conducted at room temperature (20 °C), low temperature (-20 °C), and high temperature (60 °C) environments to simulate actual operating environments of the SHM system. Guided wave generation, propagation, and sensing experiments are conducted without the support materials, and also after pasting the support materials. The wave field analysis is also conducted using the plate without support material and with support material. The study reveals that the use of TPU foil and PP laminated nonwoven fabric as support material has a very low effect on the guided wave propagation in the structure in comparison to the Kapton and PET foil. The presence of Kapton and PET also significantly influences the guided wave propagation in varying thermal environments. This makes TPU foil and PP laminated nonwoven fabric two suitable candidates as support materials for flexible PZT-based sensor systems for ultrasonic-based SHM applications.

Keywords: Structural Health Monitoring, guided waves, Lamb Waves, Kapton, polyethylene terephthalate, thermoplastic polyurethane, polypropylene laminated nonwoven fabric

Introduction

Structural health monitoring (SHM) based ultrasonic techniques are widely used for real-time damage detection in critical structural components. For ultrasonic-based SHM, piezoelectric lead zirconate titanate (PZT) transducers are employed for actuation and sensing [1, 2]. When maintaining large-scale structures (such as airframes), a number of challenges related to onboard Structural Health Monitoring (SHM) components must be overcome. These issues include the system's increased weight and cost, as well as the dependability of decision-making procedures. One way of dealing with the system weight reduction is the optimization of transducer numbers and their location [3, 4]. The additional weight, mainly due to the wiring, is a major barrier to the implementation of SHM by PZT-

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based guided wave (GW) damage detection in aircraft structures. Additional complexities are routing and fastening the wires through an intricate structure like a fuselage with frames and stringers.

Automating the installation is essential for the deployment of SHM systems on an industrial scale, such as inside a fleet of aircraft. Precision and reproducibility in sensor placement are crucial for ramping up the method in order to ensure data collection consistency. The installation must also be flexible enough to embrace components with complex geometries (such as panels with stringers, manholes, and frames) to avoid sacrificing its functionality.

When deciding between SHM and more conventional schedule-based maintenance methods, the two primary considerations are the system's added cost and reliability. In addition, the installed transducers are usually not shielded from the working environment of the aircraft, which greatly increases the chance of PZT sensor failure. The malfunction of any PZT sensor will diminish diagnostic reliability, leading to missed detections and false alarms, thereby undermining system performance [7]. So, it is necessary that the sensors withstand the operating environmental conditions and that there is a provision for easy replacement of the faulty transducer.

Additive manufacturing offers a potential answer to the previously described difficulties. Electronic device manufacturers have increasingly turned to inkjet printing, and more specifically, drop-on-demand inkjet printing, as a cost-effective and efficient production process in recent years. The flexible, non-contact printing procedure of inkjet printing makes it possible to create perfect wires on a wide variety of substrates. In recent years, inkjet printing, particularly drop-on-demand (DoD) inkjet printing, has been utilized as an efficient and economical method for the manufacturing of electronic devices. Inkjet printing is a versatile, non-contact printing process that facilitates the production of ideal wires on many substrates. This approach significantly decreases the feature size of flexible electronics. Moreover, the quantity of material necessary for circuit fabrication has drastically lowered as the material is allocated as needed [8,9]. These two essential attributes provide a substantial decrease in the production costs and weight of electrical products while simultaneously promoting environmental sustainability. Mekoprint made Polypropylene (PP) laminated nonwoven fabric is very suitable for inkjet printing for electronic devices [10]. However, it has not been tested in the sensors for SHM applications. Based on current technologies industry-scale transducer layers are available, like the integrated SHM layer by [11] and the SMART Layer by Accellent [12]. Studies have shown that the insulating coating of wires is mainly based on polymers. The polyamide, known as Kapton, was found suitable as a coating material because of its good bonding properties to composites and its good electrical insulation [5]. Recent studies have also shown the use of polyethylene terephthalate foil (PET foil), thermoplastic polyurethane foil (TPU foil), as support materials (SPM) for flexible sensors [13,14]. However, there is no study available on the suitability of these materials as support materials for piezoelectric-based SHM systems for ultrasonic-based damage detection.

The present work aims to study the suitability of PET and TPU foils as support materials for PZT-based flexible sensors for SHM applications. We have also checked the suitability of PP laminated nonwoven fabric for SHM sensor manufacturing material by using it as a support material. Specifically, the aim is to find the effect of these materials on ultrasonic-guided wave propagation in composite structures. Kapton is also used as one of the support materials for comparison. Experimental studies are conducted at room temperature (20 °C), low temperature (-20 °C), and high temperature (60 °C) environments to simulate actual operating environments of the SHM system. Guided wave generation, propagation, and sensing experiments are conducted without the support materials, and also after pasting the support materials. The wave field analysis is also conducted using the plates without support material and with support materials.

1. Experimental Setup

The experimental setup consists of five glass fiber-reinforced polymers (GFRP). Each plate was surface-mounted with four DuraAct-made piezoelectric transducers using 3M^{TM} Scotch-Weld^{TM} epoxy structural adhesive 7240 B/A (see Figure 1 (a)). Each transducer has an active element of dimension 10 mm X 10 mm X 0.5 mm. The transducers were placed at the corners of a rectangle of dimensions 200 mm X 150 mm. An NI PXI platform was used to generate ultrasonic guide waves and acquire sensor data (see Figure 1 (b)). On each plate, the transducers were actuated in a round-robin fashion, in which one transducer acts as an actuator, and the other three transducers act as sensors. The transducers were actuated with a Hann window modulated tone burst signal of amplitude 50 Vpp. Guided wave responses were collected at a central excitation frequency of 60 kHz.

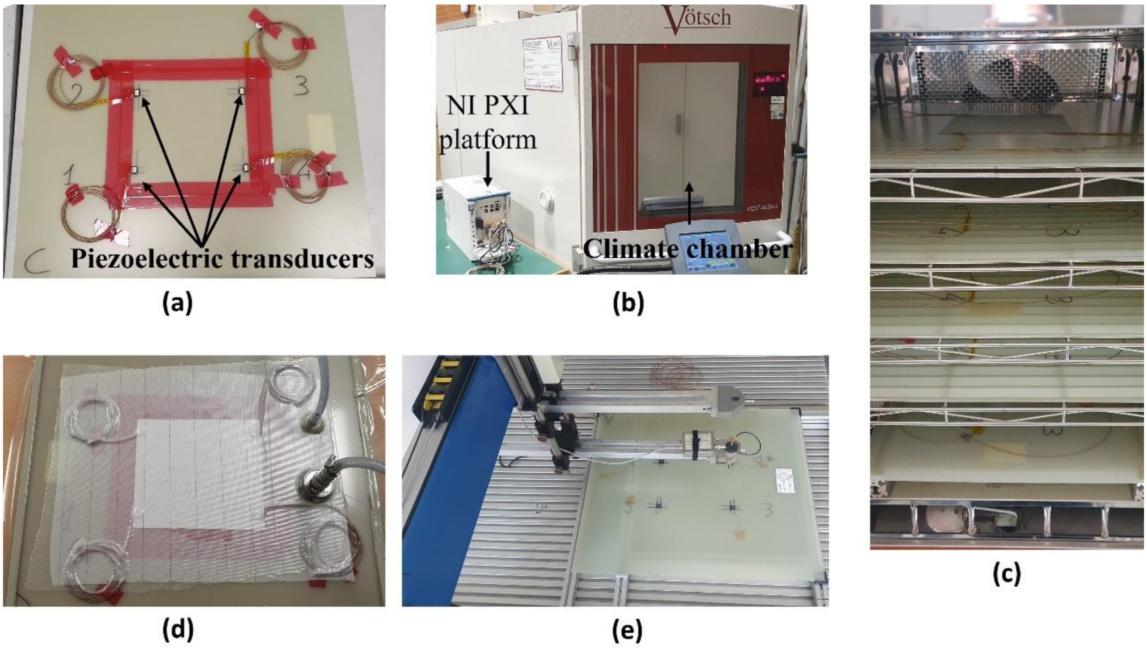

***Fig. 1**. Experimental setup (a) GFRP plate with transducers (b) NI PXI platform and climatic chamber (c) plates arranged inside climatic chamber (d) support material pasting (e) laser displacement sensor*

The guided wave responses were collected from the plates at three environmental temperatures -20 °C, 20 °C, and 60 °C at a constant humidity of 20 %. For this purpose, a climatic chamber shown in Figure 1 (b) was used. Five plates were placed inside the climatic chamber, as shown in Figure 1 (c). First, the experiments were conducted on the plate without any support material. Then, four support materials made up of Kapton, PET foil, TPU foil, and PP laminated nonwoven fabric were pasted on the plate surface covering the transducers. These support materials of dimensions 210 mm X 160 mm were pasted using a vacuum bagging procedure, as shown in Figure 1 (d). While araldite adhesive was used to paste Kapton, the other three support materials were pasted using Loctite HY 4070. The adhesives were cured for 24 hours under vacuum. Then, the experiments were repeated for these four plates with support materials.

2. Results and Discussion

2.1 Effect of Support Materials at Room Temperature

The guided wave response obtained from the plate before applying the support material (baseline signal) and after applying the support material (current signal) is compared in Figure 2 for a central excitation frequency of 60 kHz. The data presented here are for the path of length 150 mm. It has been observed that the presence of the support material changes the amplitude and time of arrival of both the fundamental symmetric (S_0) and antisymmetric (A_0) modes. For all the support material cases considered here, the time of flight (ToF) increases. The increase in the ToF in the case of Kapton is higher in comparison to other support materials. The higher thickness of the Kapton layer and the use of Araldite for adhesion could be contributing factors, altering the entire system's elastic moduli and density. It may be because of the change in the elastic modulus and density of the overall system, since the thickness of the Kapton layer is higher, and Araldite is used for adhesion. In addition, it has been noted that in the cases of Kapton, PET, and TPU, the amplitude of the S_0 mode increased while the amplitude of the A_0 mode decreased. However, in the case of the PP laminated nonwoven fabric as the support material, the amplitude increased for both S_0 and A_0 mode waveforms.

It has been found that the change in the amplitude and ToF, when TPU is the support material, is very low compared to other materials. This makes TPU a suitable material to be used for smart sensors, which will have a very low effect on the GW propagation in the structure.

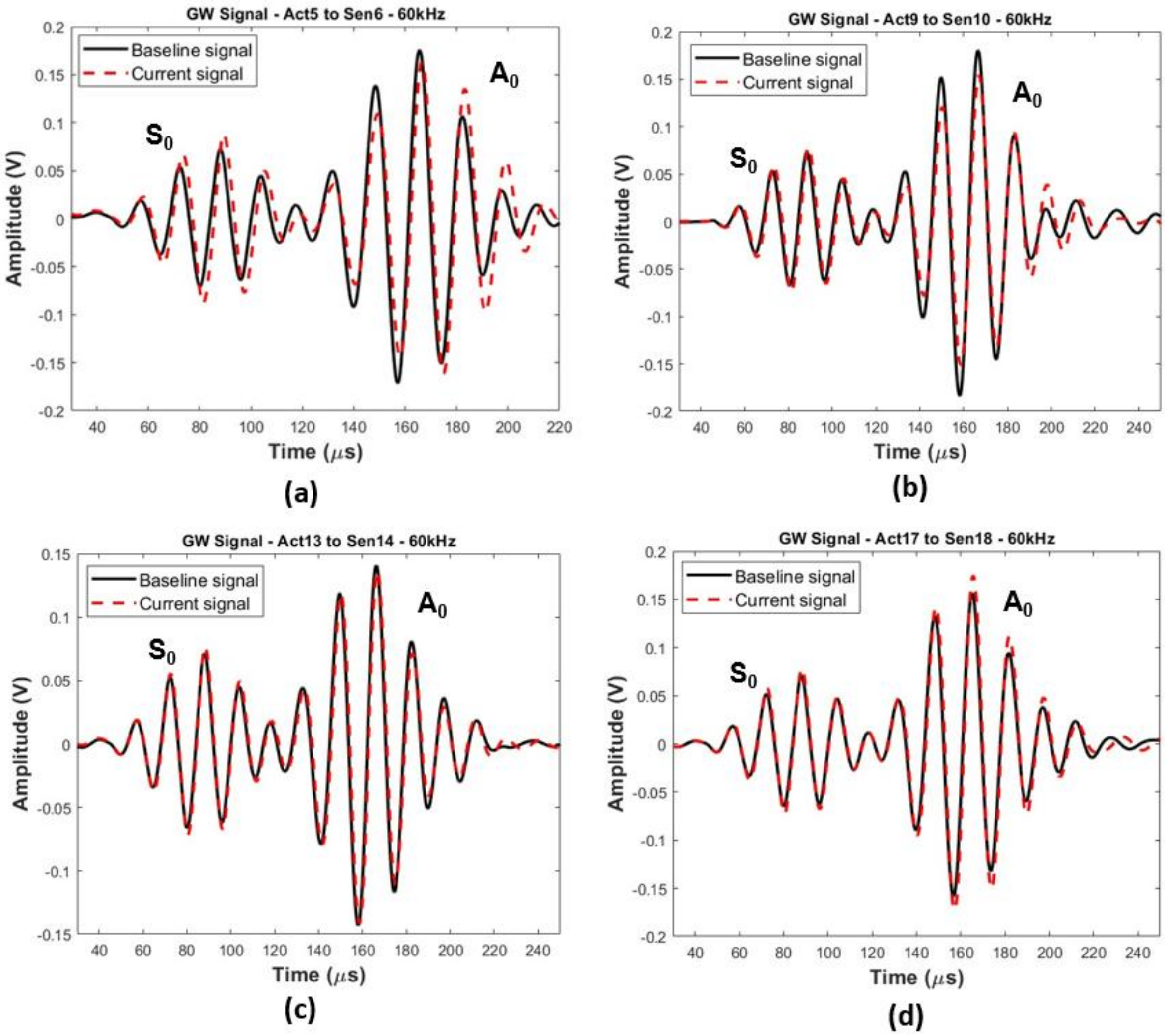

Fig. 2. *Comparison of Lamb wave response before and after pasting support materials at an excitation frequency of 60 kHz for support materials as (a) Kapton (b) PET (c) TPU (d) PP laminated nonwoven fabric*

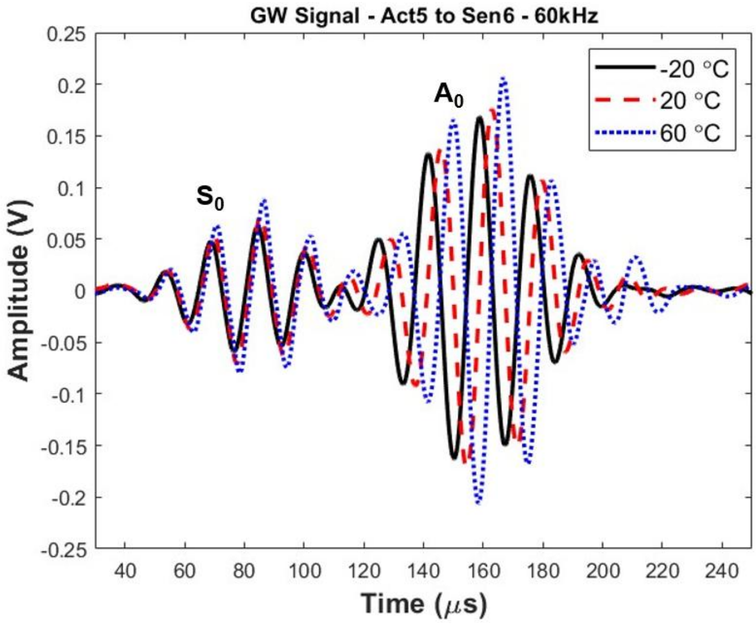

Fig. 3. *Comparison of Lamb wave response for three environmental temperatures at an excitation frequency of 60 kHz*

2.2 Effect of Temperature on Lamb Wave in GFRP Plate

The impact of temperature variation on the GW response is analyzed by comparing the responses recorded at 20 °C, -20 °C, and 60 °C, as illustrated in Figure 3, for an excitation frequency of 60 kHz. The GW response's amplitude and ToF are found to vary with temperature. With the increase in the temperature from -20 °C to 60 °C, the amplitude and ToF increased. The cause of the change in the amplitude is the change in the piezoelectric strain coefficient and dielectric permittivity and mechanical properties of the transducers, the degradation of the adhesive layer, and the change in the elastic moduli of the GFRP. The change in the ToF can be attributed to the change in the wave velocity due to variations in the elastic moduli and density of the plate. The change in the sensing path length due to the thermal expansion/contraction of the plate also contributes to the change in ToF.

2.3 Influence of Support Materials on Lamb Waves under Thermal Environments

The main aim of this study is to find out the influence of the presence of the support materials on the guided wave response under varying thermal environments.

2.3.1 Influence on Lamb Waves Amplitude

Figure 4 (a) compares the relative peak amplitude of the S_0 mode at lower and elevated temperatures with respect to the amplitude at ambient temperature 20 °C. The comparisons are shown for the plates with support materials. A similar comparison for the A_0 mode amplitude is presented in Figure 4 (b). The peak amplitude of the S_0 and A_0 modes of a signal is obtained by taking the peak of the Hilbert envelope of the corresponding waveforms of the signal. The amplitude obtained for lower and elevated cases is normalized with respect to the amplitude obtained at ambient conditions. The normalized amplitude is obtained for the same plate with and without support material separately and compared.

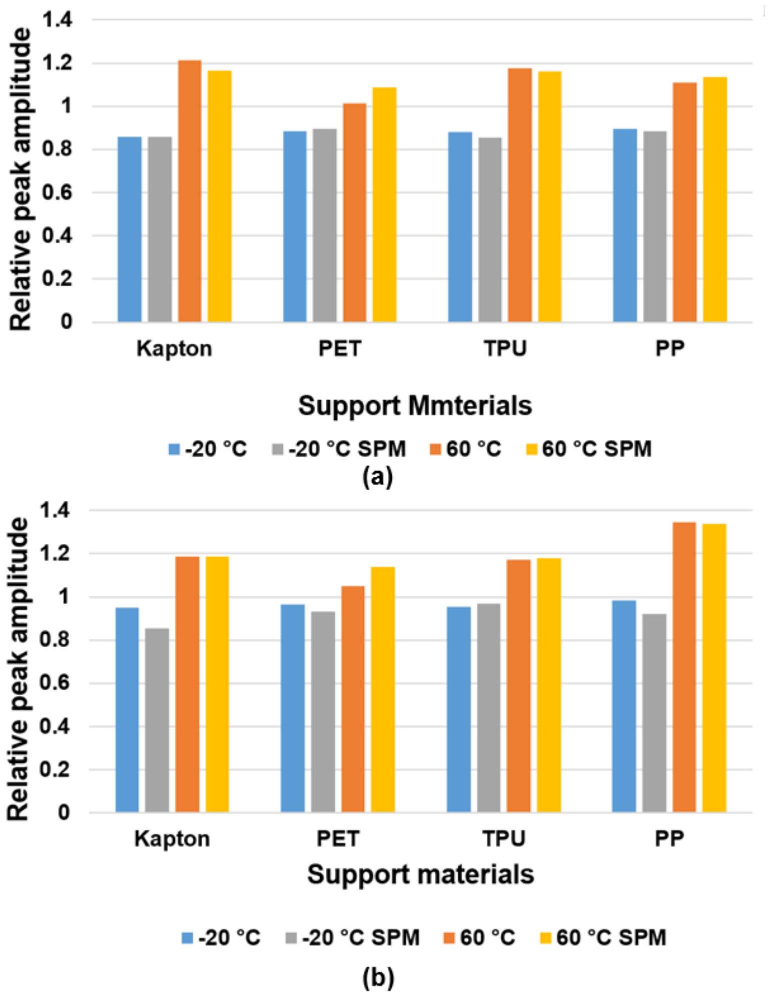

Fig. 4. *Comparison of the influence of temperature on the amplitude of Lamb waves (a) S_0 mode, and (b) A_0 mode, for the plates with and without support materials attached.*

It has been observed from Figure 4 (a) that for the S_0 mode, the relative amplitude at 60 °C obtained from the plate before and after pasting the support material has a higher variation in comparison to the relative amplitude obtained at -20 °C. In the case of the A_0 mode shown in Figure 4 (b), there is significant variation in the relative amplitude obtained before and after pasting the support material at both lower and elevated temperatures. With the observation from Figure 4, it can be stated that the presence of Kapton and PET as support materials has a higher influence on the Lamb waves amplitude in comparison to TPU and PP laminated nonwoven fabric under varying thermal environments.

2.3.2 Influence on Lamb Waves Time of Flight

The change in the ToF of S_0 and A_0 modes of guided wave due to the decrease and increase in the temperature from the ambient temperature (20 °C) is presented in Figure 5. The change in ToF obtained before and after pasting the support materials is presented for comparison. The change in the ToF is obtained by subtracting the ToF of wave modes obtained at 20 °C from that obtained at -20 °C and 60 °C. It is observed that the presence of support material influences the ToF of guided wave modes. Support materials have a higher influence on the A_0 mode ToF than that of the S_0 mode. Further, support materials like Kapton and PET have a higher influence on the guided wave ToF under varying thermal environments. So, support materials like TPU and PP laminated nonwoven fabric can be used for smart sensor layers that will have a very low impact on guided wave propagatio propagation.

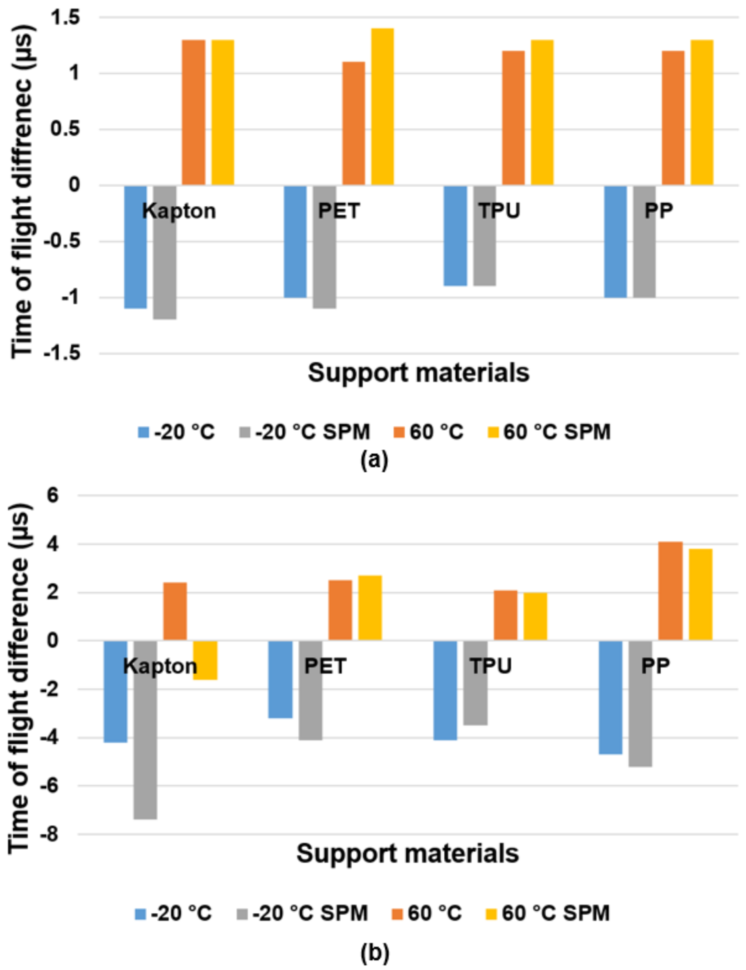

Fig. 5. *Comparison of the influence of temperature on the time of flight of Lamb waves (a) S0 mode, and (b) A0 mode, for the plates with and without support materials attached.*

3. Conclusions

A detailed study has been conducted to examine the suitability of the PET, TPU, and PP laminated nonwoven fabric for the fabrication of smart PZT sensors used for ultrasonic-guided wave-based SHM applications. Guided wave propagation experiments have been performed in a system of GFRP plates with surface-mounted PZT transducers before and after pasting the support materials at room temperature (20 °C), lower temperature (-20 °C), and elevated temperature (60 °C). The study has revealed the following:

1. The presence of the support material changes the amplitude and time of arrival of both the fundamental symmetric (S_0) and antisymmetric (A_0) modes. The change in the amplitude and ToF, when TPU is the support material, is very low compared to other materials. This makes TPU a suitable material to be used for smart sensors, which will have a very low effect on the guided wave propagation in the structure.
2. For a system of GFRP plates with surface-bonded PZTs, with the increase in the temperature from -20 °C to 60 °C, the amplitude and time of flight of the propagating guided wave increase.
3. The presence of Kapton and PET as support materials has a higher influence on the Lamb waves amplitude in comparison to the presence of TPU and PP laminated nonwoven fabric under varying thermal environments.

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4. Support materials like Kapton and PET have a stronger influence on the guided wave ToF under varying thermal environments.

It can be concluded from this study that support materials like TPU and PP laminated nonwoven fabric can be used for the fabrication of PZT-based SHM sensors that will have a very low impact on the ultrasonic guided wave propagation.

Acknowledgments

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