Curing Monitoring of Composite Patch Using Electromechanical Impedance

---

JINSHAN WEN, JIANJIAN ZHU, YISHOU WANG
and XINLIN QING

ABSTRACT

The repair technology of surface-bonded composite patches has garnered significant attention in the engineering field. The quality of the repair is directly impacted by the curing degree of the patch. Thus, monitoring the curing process of the patches is necessary. This paper proposes a real-time monitoring method for the curing of composite patches based on electromechanical impedance (EMI) technology. The proposed method can accurately track the curing process of composite patches. A piezoelectric sensor was embedded in T300 woven carbon fiber prepreg, and EMI signals were collected at 2-minute intervals during the curing process. Dielectric analysis (DEA) was performed to verify the effectiveness and feasibility of the method. The resonant resistance and correlation coefficient (CC) index were utilized to characterize the curing process of the patches. The experimental results demonstrate that the resonant resistance remains stable when the resin is converted to approximately 85%. The development trend of the CC aligns with the curing behavior of the resin, and the rate of change of the CC can reflect the speed of resin conversion. Furthermore, the proposed method can accurately monitor the curing process of both the carbon fiber prepreg patches and those bonded to an aluminum plate, demonstrating the universality of this method.

Key word: composite patch; piezoelectric sensor; electromechanical impedance; curing monitoring

INTRODUCTION

Surface-applied composite patch is a cost-effective and easy-to-operate method for repairing metallic and composite structures, and has been widely adopted in the aerospace field due to its advantages [1]. This method is particularly effective in preventing damage propagation, restoring structural strength and stiffness, without significantly introducing additional weight and creating new holes in the structure. Previous studies have shown that the quality of a repaired structure is significantly influenced by the shape, thickness, and lay-up of the patch [2-3]. Moreover, the curing quality of composite patches is a crucial factor determining the repair performance of damaged structures [4]. Since the curing degree of composite patches directly impacts the curing quality, accurately assessing the degree of curing is of great significance.

In recent years, structural health monitoring (SHM) has emerged as an effective means of maintaining the safety of composite structures [5-6]. Unlike NDT, SHM is an on-line monitoring method capable of providing real-time information about the state of the inspected structure, making it well-suited for curing monitoring of composites. Electromechanical impedance (EMI) based on piezoelectric (PZT) sensors is a typical SHM technique that offers the advantages of simple installation and high sensitivity [7], making it particularly advantageous for composite curing monitoring. Moreover, EMI requires only one sensor to perform the measurement, which is more suitable for monitoring the curing process of small-sized patches compared to ultrasonic guide wave that require at least two sensors.

Jinshan Wen, Jianjian Zhu, Yishou Wang, Xinlin Qing. School of Aerospace Engineering, Xiamen University, No.4221-134, Xiang'an South Road, Xiamen, Fujian, China

EMI has shown promising results in monitoring the strength development during cement curing [8-9]. Recently, scholars have gradually investigated the application of EMI for curing monitoring of resin matrix composites. Lim et al. [10] demonstrated that EMI technique can effectively monitor the curing process of structural adhesives. Zhang et al. [11] embedded PZT in flax-reinforced bio-epoxy resin and showed that EMI can effectively monitor the reaction process. Moreover, Tang et al. [12] proposed a finite element analysis model based on EMI and utilized it to predict the Young's modulus and strength of the adhesive during the curing process.

The studies mentioned above have demonstrated the potential and feasibility of using EMI for monitoring the curing of composites. However, most of these studies have only focused on a single curing scenario. Therefore, this paper proposes an EMI-based curing monitoring method that can effectively monitor the curing process of resins under different curing conditions. Embedding PZT in the specimens to obtain EMI signatures, and the resonance resistance and correlation coefficient (CC) were used to characterize the curing process of the resin. Dielectric analysis (DEA) has been proven to be an effective method for monitoring the curing behavior of composites [13]. Therefore, DEA tests were performed simultaneously during the experiments to verify the effectiveness and accuracy of the method proposed. Two set of experiments were conducted for curing carbon fiber prepreg patches and curing carbon fiber prepreg patches pasted on an aluminum plate, and the results showed that the curing process of composite patches was well monitored by using EMI.

MONITORING PRINCIPLE

The EMI technology utilizes the impedance signal of the coupling between the PZT and the structure to reflect the structural state information. The same PZT acts as both an exciter and a receiver. To reveal the interaction mechanism between the circular PZT sensor and the structure, Zhu et al. [14] developed a coupling model for circular PZT (with a radius of *a* and thickness of *h*) with the structure and derived the corresponding admittance expressions:

$$Y = \mathrm{j}\omega \frac{\pi a^2}{h}\left[\varepsilon_{33}^{T} - \frac{2d_{31}^2}{s_{11}^{E}(1-\nu)}\right] + \mathrm{j}\frac{\pi a}{h} \cdot \frac{4c_{\mathrm{p}} d_{31}^2}{s_{11}^{E}(1-\nu)} \cdot \frac{J_1(\kappa a)}{J_0(\kappa a)} \cdot \frac{Z_{\mathrm{P,sc}}}{Z_{\mathrm{P,sc}} + Z_{\mathrm{str}}} \tag{1}$$

where the Y is the admittance, j is an imaginary unit, ω is the frequency of the excitation signal; ε_{33}^{T} denotes dielectric permittivity, d_{31} denotes piezoelectric strain coefficient, s_{11}^{E} denotes the elastic compliance coefficient, ρ denotes the sensor density; ν means the planar Poisson's ratio, c_{p} means the wave velocity, $J_0(\cdot)$ and $J_1(\cdot)$ is the 0-order and 1-order Bessel function of the first kind, respectively, κ means the wavenumber; $Z_{\mathrm{p,sc}}$ expresses the PZT short-circuit impedance and Z_{str} expresses the equivalent impedance of the structure.

Equation (1) shows that the equivalent impedance of the coupling system is affected by both the sensor parameters and the equivalent mechanical impedance of the structure. As the physical properties, including strength and stiffness, of the composite patches change during the curing process, the equivalent mechanical impedance of the structure also changes. Therefore, the curing degree of the patches can be evaluated based on the pattern of changes in the impedance signals.

Previous studies indicated that the real part of the impedance signal, i.e., the resistance signal, is more sensitive to the structural alterations. Therefore, the resistance signal is used for analysis. The CC metric is utilized to characterize the curing process of the composite patch and its expression is given by:

$$CC = \frac{1}{N\sigma_0\sigma_1}\sum_{k=1}^{N}(R_0 - \overline{R_0})(R_1 - \overline{R_1}) \tag{2}$$

where N is the number of data, R_0 is the baseline data, R_1 is the other data sets from the curing process. $\overline{R_0}$ and $\overline{R_1}$ denote the mean of R_0 and R_1, respectively. σ_0 and σ_1 express the standard deviation of R_0 and R_1, respectively. As the deviation of the signal from the baseline increases, the CC will decrease.

MATERIALS AND METHODS

Experimental Materials

In our experiments, the IDEX 115F sensor was utilized for DEA testing, while EMI testing was conducted using a circular PZT model PZT-5A (with dimensions of 8× 0.5 mm). The SMART Layer proposed by Stanford University was applied to connect the PZT, which is a structure that allows for easy connection of embedded sensors and effectively prevents short-circuiting of the PZT during the patch curing process [15]. The composite patches utilized in the study were composed of 12 layers of T300 prepreg, which dimensions are 100×100×0.3 mm.

Experimental Setup

The specimens were cured using NETZSCH DEA 288 Press mini hot press, which applies pressure and heat according to the curing conditions presented in Table 1.

The curing of composite patches was monitored under two curing conditions:

Case I: The specimens underwent direct curing on the heating stage. The PZT was embedded between the 6th and 7th layers of the specimen, while the IDEX 115F was positioned at the edge of the same layer, as illustrated in Figure 1(a).

Case II: To simulate a structural repair scenario, the patch was affixed to a 6061-aluminum alloy plate with the size of 200×200×5 mm, and then the aluminum plate was placed on a heating platform for heating. To investigate the effect of sensor placement on the monitoring results, the PZT was embedded between the aluminum

TABLE I. SETTING OF CURING CONDITIONS

Curing pressure /N	Initial temperature /°C	Termination temperature/°C	Temperature rise rate /(°C/min)	Curing time /min
1000	20	120	5	170

alloy plate and the prepreg patch, while the IDEX 115F was embedded at the edge position of the patch, as shown in Figure 1(b).

EMI testing was performed using the Wayne Kerr WK6500B Precision Impedance Analyzer. An alternating voltage of 1 V was applied to the PZT, and data were collected at 1 kHz intervals in the frequency range of 150-450 kHz, with a signal acquisition interval of 2 min. The identical curing conditions and signal acquisition settings were applied to both sets of experiments.

EDA Testing

DEA tests were performed simultaneously during the experiments for comparison with EMI results. The NETZSCH DEA 288 Dielectric Cure Monitor was employed for data acquisition. The experimental platform consisting of the EMI monitoring system and the DEA monitoring system together is shown in Figure 2.

The DEA test outcomes indicate that the heating platform temperature reached the pre-set value of 120°C at 20 min, and the temperature remained constant for 150 min, as shown in Figure 3. Comparing the DEA results under the two curing conditions, it is observed that the resin curing rate in Case II is slower than that in Case I. The reason is that the aluminum plate dissipates heat more quickly during the curing process, causing the resin to absorb less heat and resulting in a lower curing rate.

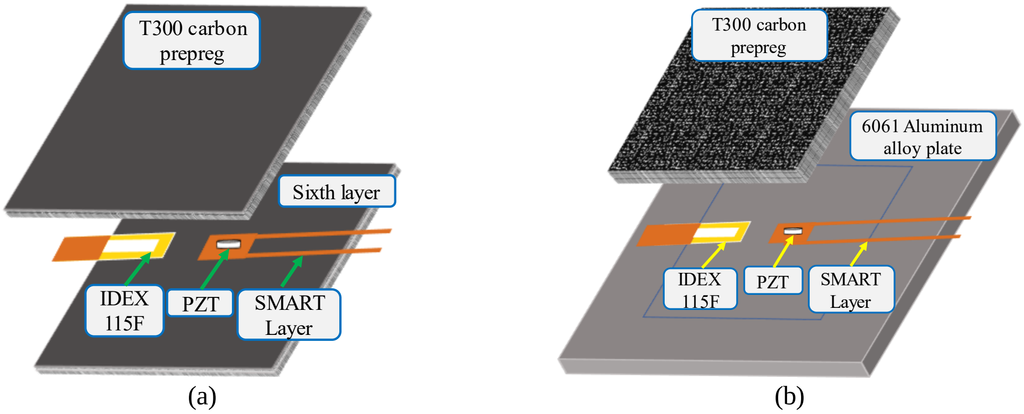


Figure 1 Schematic diagram of the curing of the composite patch: (a)Case I (b) Case II

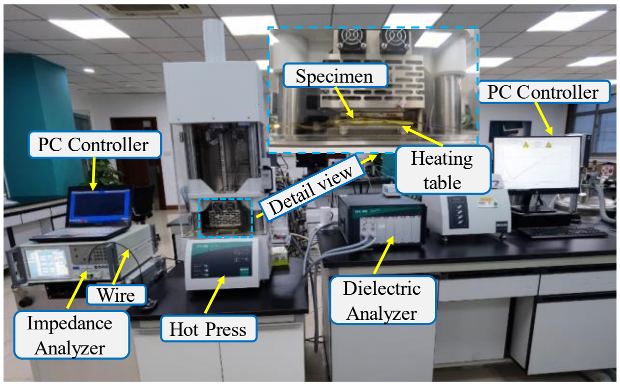
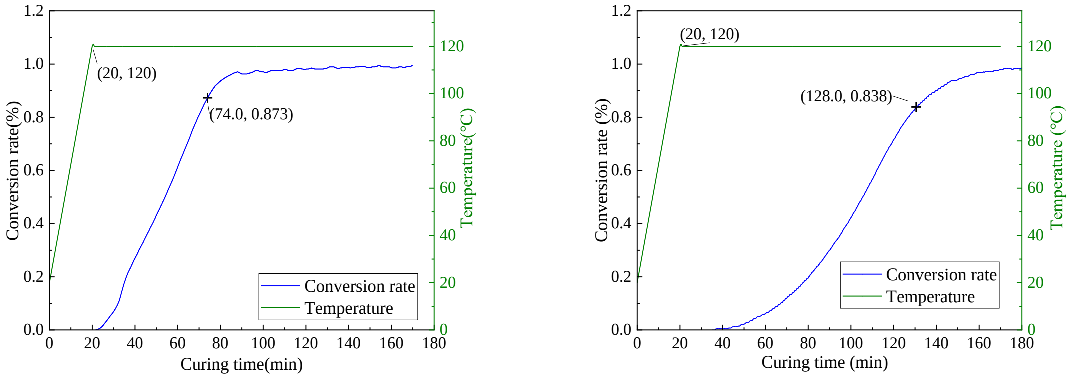


Figure 2 Curing monitoring experimental platform



(a) (b)

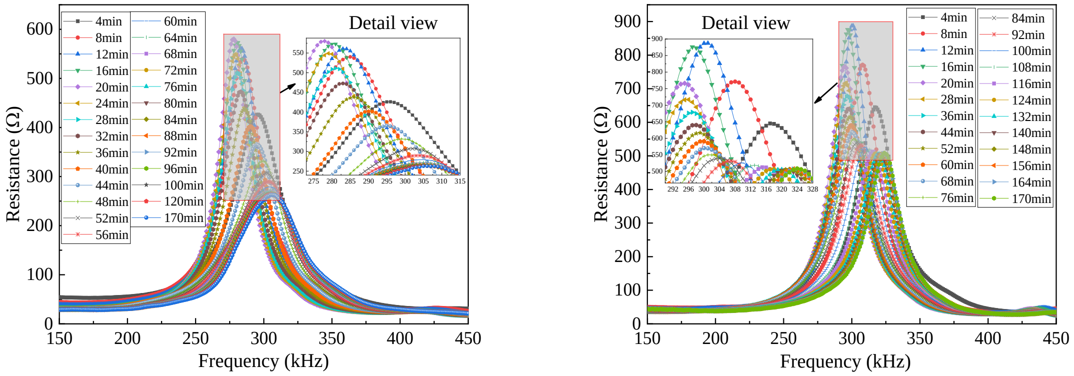
Figure 3 DEA test results for composite patch (a)Case I (b) Case II

RESULTS AND DISCUSSION

Monitoring Signals

For both sets of experiments, the resistance signatures were obtained at 2-min intervals, resulting in the acquisition of 85 sets of data for each experiment. To facilitate the observation of the signal variation pattern, only a subset of the signal curves was selected for plotting. In Case I, a set of signals was chosen at 4-min intervals for plotting, as depicted in Figure 4(a), since the signal curves exhibited faster shifts. In Case II, a set of signals was selected at 8-min intervals for plotting, as illustrated in Figure 4(b), as the signal curve shifts were slower.

Figure 4 shows that there is a significant peak in the signal curve for all curing states within the test frequency range. During the heating phase, the signal characteristic peak is gradually shifted to the upper left due to the temperature rise and resin melting. During the constant temperature phase, the cross-linking reaction within the resin enhances the stiffness of the structure, causing a gradual shift of the signal characteristic peak towards the lower right. When the resin is fully cured, the resistance signals tend to stabilize. The resistance signals demonstrate a similar variation pattern under both curing conditions, indicating that EMI is effective in monitoring the curing process of carbon fiber patches.



(a) (b)

Figure 4 Resistance signal curves in the curing process (a)Case I (b) Case II

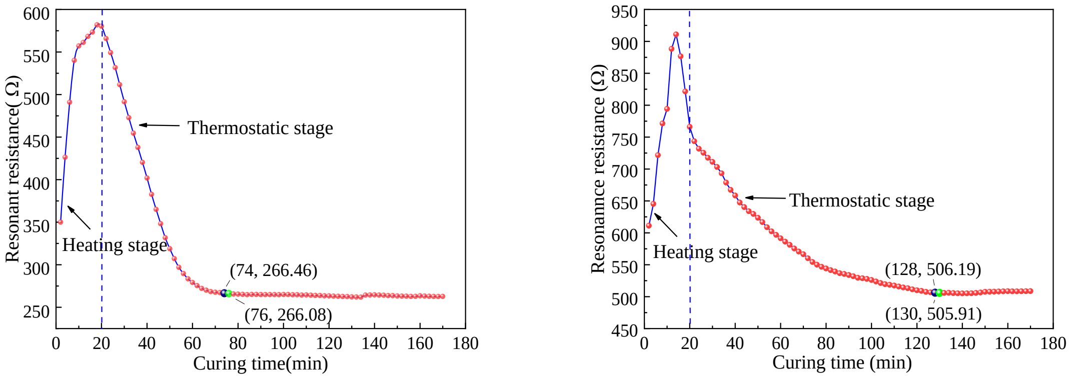
The resonance resistance is extracted from the signal and plotted against the cure time in Figure 5. The resonance resistance tends to increase first and then decrease during the heating phase. However, in Case II, the resonance resistance decreases earlier due to the sensor is pasted between the aluminum plate and the composite patch, and the aluminum plate dissipates heat faster, which leads to the resin on the surface of the aluminum plate melts earlier. During the constant temperature phase, the resonance resistance decreases with increasing stiffness of the resin.

In Case I, the difference between the resonance resistance values at 74 min and 76 min is only 0.38 Ω, which is within the measurement error of 0.5 Ω specified in the technical data sheet of the impedance analyzer. Therefore, it is concluded that the resonance resistance stabilizes after 74 min. In Case II, the difference between the resonance resistance values at 128 min and 130 min is 0.28 Ω. Hence, the resonance resistance is considered stable after 128 min. The resin conversion rate is 87.3% and 83.8% when the resonance resistance value remains stable, respectively, in combination with Figure 3. Consequently, the resonance resistance value is considered to remain stable when the resin conversion rate reaches about 85%.

Curing Characterization Based on CC Metric

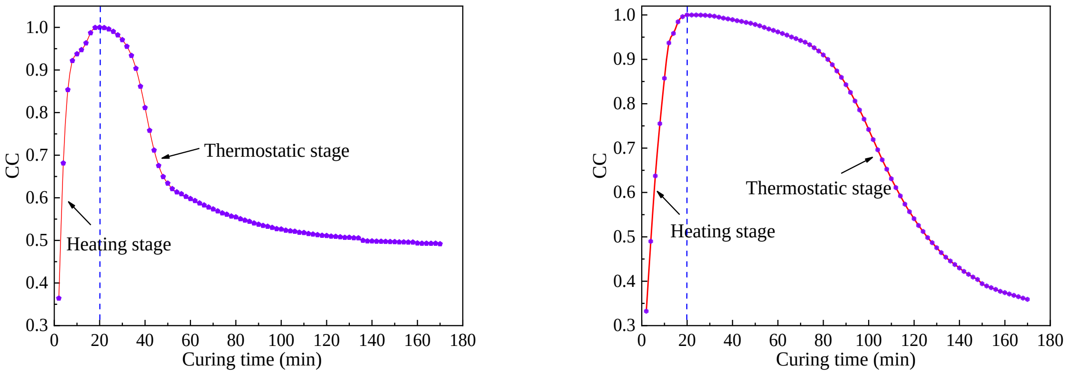
To provide a more intuitive reflection of the resin curing process, CC is adopted to quantitatively characterize the curing process of the resin. The temperature reaches the setup value 20 min after the start of curing and the EMI signal is almost unaffected by the temperature, so the signal obtained at 20 min is selected as the baseline. The CC values are separately calculated for the two curing cases, and the CC versus curing time is plotted as shown in Figure 6.

The heating phase resulted in a significant variation in the CC metrics due to temperature changes and resin melting cause a dramatic shift in the resistance signals. During the constant temperature phase, the CC value decreases slowly initially, suggesting minimal changes in resin stiffness while in a liquid state. Subsequently, the CC value began to decrease at a faster rate, indicating an increase in resin curing rate and intensification of structural stiffness modification. Eventually, the CC value reached a stable state, demonstrating that the resin has fully cured and the variation in



(a) (b)

Figure 5 Resonant resistance curves with curing time (a)Case I (b) Case II



(a) (b)

Figure 6 CC curves with curing time (a)Case I (b) Case II

structural stiffness is small. The CC curve development patterns in both curing cases matched the resin curing behavior, affirming the ability of the CC index to effectively characterize the resin curing process.

Comparing the CC curves of the two curing cases, it is evident that the CC curve for Case II exhibits a slower rate of change, suggesting a relatively lower resin curing rate. The accuracy of this finding can be corroborated through the results of the DEA test.

CONCLUSIONS

This paper presents a study on monitoring the curing process of composite patches using EMI, and the accuracy of the results is confirmed by DEA testing. The experiments were conducted for two cases of curing carbon fiber prepreg patches and curing carbon fiber prepreg patches affixed to an aluminum plate. The resistance signal curves exhibited similar trends during the curing process, indicating the viability of the EMI technique for monitoring composite patch curing. Additionally, the study characterized the patch curing process by analyzing resonance resistance and CC metrics. The results showed that the resonance resistance remained constant at approximately 85% resin conversion, while the CC metric accurately reflected the resin conversion rate.

This study demonstrates the effectiveness of the EMI method in monitoring the curing process of composite patches under different curing conditions. Further investigations are required to determine the degree of resin cure.

REFERENCES

[1] Zhou, W., X. Ji, S. Yang, J. Liu, and L. Ma. 2021. "Review on the Performance Improvements and Non-destructive Testing of Patches Repaired Composites," *Composite Structures*, 263:113659.

[2] Li, C., Q. Zhao, J. Yuan, Y. Hou, and Y. Tie. 2019. "Simulation and Experiment on the Effect of Patch Shape on Adhesive Repair of Composite Structures," *Journal of Composite Materials*, 53:4125 - 4135.

[3] Maleki, A., M. Saeedifar, M. Ahmadi Najafabad, and D. Zarouchas. 2019. "The Fatigue Failure Study of Repaired Aluminum Plates by Composite Patches Using Acoustic Emission," *Engineering Fracture Mechanics*, 210:300-11.

[4] Zhang, J., X. Cheng, J. Zhang, X. Guo, and W. Huang. 2019. "Effect of Curing Condition on Bonding Quality of Scarf-repaired Composite Laminates," *Chinese Journal of Aeronautics*, 33:2257-2267.

[5] Jang, B.W., and C. Kim. 2017. "Real-time Detection of Low-velocity Impact-induced Delamination Onset in Composite Laminates for Efficient Management of Structural Health," *Composites Part B-engineering*, 123:124-135.

[6] Qing, X., W. Li, Y. Wang, and H. Sun. 2019. "Piezoelectric Transducer-Based Structural Health Monitoring for Aircraft Applications," *Sensors (Basel, Switzerland)*, 19.

[7] Na, W.S., and K. Park. 2017. "A Cost-effective Impedance-based Structural Health Monitoring Technique for Steel Structures by Monitoring Multiple Areas," *Journal of Intelligent Material Systems and Structures*, 28:154 - 162.

[8] Choi, S., N. Tareen, J. Kim, S.H. Park, and I. Park. 2018. "Real-Time Strength Monitoring for Concrete Structures Using EMI Technique Incorporating with Fuzzy Logic," *Applied Sciences*, 8:75.

[9] Lim, Y.Y., S.T. Smith, R.V. Padilla, and C.K. Soh. 2019. "Monitoring of Concrete Curing Using the Electromechanical Impedance Technique: Review and Path Forward," *Structural Health Monitoring*, 20: 604 - 636.

[10] Lim, Y.Y., Z.S. Tang, and S.T. Smith. 2019. "Piezoelectric-based Monitoring of the Curing of Structural Adhesives: A Novel Experimental Study," *Smart Materials and Structures*, 28.

[11] Zhang, M., O. Bareille, and M. Salvia. 2019. "Cure and Damage Monitoring of Flax Fber-Reinforced Epoxy Composite Repairs for Civil Engineering Structures Using Embedded Piezo Micro-patches," *Construction and Building Materials*.

[12] Tang, Z.S., Y.Y. Lim, S.T. Smith, and R.V. Padilla,. 2020. "Modelling of the Electromechanical Impedance Technique for Prediction of Elastic Modulus of Structural Adhesives," *Structural Health Monitoring*, 20:2245 - 2260.

[13] Hardis, R., J.L. Jessop, F.E. Peters, and M.R Kessler. 2013. "Cure Kinetics Characterization and Monitoring of An Epoxy Resin Using DSC, Raman Spectroscopy, and DEA," *Composites Part A-applied Science and Manufacturing*, 49:100-108.

[14] Zhu, J., Y. Wang, and X. Qing. 2019. "A Novel Electromechanical Impedance Model for Surface-bonded Circular Piezoelectric Transducer," *Smart Materials and Structures*, 28.

[15] Rocha, H., C.O. Semprimoschnig, and J.P. Nunes. 2021. "Sensors for Process and Structural Health Monitoring of Aerospace Composites: A Review," *Engineering Structures*, 237:112231.