

Development of a New Temporary Attachment Technique for Detecting Debonding of a Composite Structure Using Impedance Based Non-Destructive Testing Method

Dong-Woo Seo ¹, Kyu-San Jung ¹, Yi-Seul Kim ², Hyung-Jin Kim ² and Wongi S. Na ^{2,*}

¹ Korea Institute of Civil Engineering and Building Technology (KICT), Goyang-si 10223, Korea; dwseo@kict.re.kr (D.-W.S.); jungkyusan@kict.re.kr (K.-S.J.)

² Department of Civil Engineering, Seoul National University of Science and Technology, Seoul 01811, Korea; dltnf3131@seoultech.ac.kr (Y.-S.K.); hyungjin4843@naver.com (H.-J.K.)

* Correspondence: wongi@seoultech.ac.kr

Abstract: To date, the application of composite materials has been used throughout the globe due to its advantages, such as corrosion resistance, high strength, design flexibility, and light weight. However, the joining of composite materials is usually achieved with adhesives, where debonding of parts can cause unexpected failure. Thus, detecting and locating defects due to impact or fatigue stresses at an early stage is crucial to ensure safety. Various non-destructive testing (NDT) techniques have been used to detect defects in composite structures, where this study proposes an improved approach of using one of the NDT techniques to detect and locate debonding of glass fiber epoxy plates. Here, the electromechanical impedance (EMI) technique is used with a new way of detecting defects using a movable device. This idea could reduce the overall cost of the monitoring system as the conventional EMI technique requires one to permanently attach a large number of piezoelectric transducers when monitoring large structures. The performance of the proposed idea is tested against another temporary attachment method to investigate the possibility of using the new idea for monitoring debonding in composite structures.

Keywords: piezoelectric transducer; non-destructive testing; debonding; composite materials; damage detection



Citation: Seo, D.-W.; Jung, K.-S.; Kim, Y.-S.; Kim, H.-J.; Na, W.S. Development of a New Temporary Attachment Technique for Detecting Debonding of a Composite Structure Using Impedance Based Non-Destructive Testing Method. *Appl. Sci.* **2021**, *11*, 10763. <https://doi.org/10.3390/app112210763>

Academic Editor:
Giuseppe Lacidogna

Received: 14 October 2021
Accepted: 12 November 2021
Published: 15 November 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Glass fiber reinforced epoxy is one of the composite materials used throughout the globe for its advantages, such as corrosion resistance, high strength, light weight, and design flexibility [1]. Although composites are more expensive compared to common metals, such as aluminum and steel, new applications are increasing with time in various fields, including aerospace and civil structures. Composite material is more difficult to evaluate in terms of quality control than traditional materials (such as steel) as it is made with materials with different mechanical properties. When using composites, defects, such as debonding, delamination, and cracks, can occur due to impact or fatigue stresses, and detecting these damages at an early stage is critical to ensure safety. For detecting damage, various non-destructive testing (NDT) techniques have been developed for testing composite structures. Damage detection methods can be categorized into contact and non-contact methods, where contact methods include electromagnetic testing, eddy current testing, and ultrasonic testing [2–5]. Non-contact methods include holography, infrared, and thermography. It is usually used for situations where physical contact between the target structure and sensor is not possible [6–8].

In this study, a new way of conducting one of the contact methods known as the electromechanical impedance (EMI) technique is investigated. The EMI technique requires one to permanently attach the piezoelectric transducer onto the target where an impedance

measuring device is used to measure impedance, usually before and after damage, to identify the existence of damage [9–12]. Permanently attaching the PZT transducer can allow one to monitor a structure in real-time. However, for large structures, it can be costly as the sensing range of the EMI technique is small, and many PZT transducers would be required. Thus, to overcome this problem, attempts have been made to create the EMI technique that allows one to temporarily attach a PZT transducer to cover a large area with a single PZT device [13]. Although more research is required to solve the existing problem of the temporary attachment EMI technique, the previous research required one to attach and detach the PZT device manually. In this study, the proposed roller device is designed to be simply rolled onto the surface of a composite structure for detecting damage. Here, tests were conducted to evaluate the performance of the proposed idea against one of the temporary attachment PZT devices mentioned previously.

2. Temporary Attachment Methods with the EMI Technique

The experimental setup for this study is shown in Figure 1, where the AD5933 evaluation board was connected to the computer with the software provided by the provider, Analog Devices Co., (Norwood, MA, USA). The software performed the EMI technique, which measured the electrical impedance of the PZT transducer (model 5A4E, purchased from Piezo.com, accessed on 13 October 2021, Woburn, MA, USA). Here, Equation (1) shows that electrical admittance (the inverse of impedance), $Y(\omega)$ directly relates to the mechanical impedance of the structure, $Z_s(\omega)$, and the attached PZT transducer, $Z_a(\omega)$. This means that any changes in the structure will change its mechanical impedance, which can be detected by monitoring the electrical impedance of the attached PZT patch [14]. Rest of the variables in the equation I , V , ω , a , ϵ_{33}^T , δ , d_{3x} , $\bar{Y}_{xx}^E$ are the PZT output current, PZT input voltage, input frequency, geometric constant, dielectric constant, loss tangent, piezoelectric constant, and Young's modulus, respectively.

$$Y(\omega) = i\omega a \left(\epsilon_{33}^T (1 - i\delta) - \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} d_{3x}^2 \bar{Y}_{xx}^E \right) \quad (1)$$

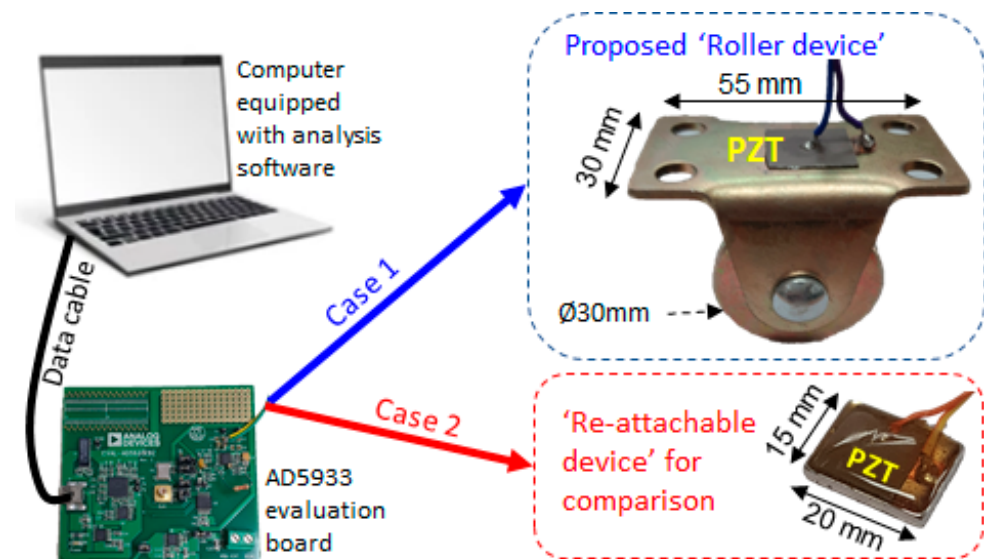


Figure 1. Photo of both temporary attachment devices with AD5933.

The AD5933 evaluation board can measure impedance up to 100 kHz with 500 data points where it is fully powered by the data cable. For this study, the new concept of using a roller device labeled 'Case 1' in Figure 1 was investigated. The top surface was 55 mm × 30 mm which is wide enough for a 15 mm square PZT to be attached, as shown in the figure. The wheel located at the bottom, with a diameter of 30 mm, allowed the device to be moved freely on any surface. The performance of this 'roller device' was tested

in the next section to investigate the possibility of the proposed idea. Since the device was made of metal, the vibrations from the PZT transducer should be enough to travel to the bottom of the wheel to detect defects. To compare this idea with another temporary attachment method, a 15 mm × 20 mm metal (3 mm thickness) with a 13 mm square PZT attached on top was used to evaluate the performance difference between the two cases. The major difference between the two cases was that the ‘re-attachable device’ of case 2 required one to use a double-sided tape to detect damage. This can be time-consuming for large composite structures. On the other hand, the roller device (case 1) just needed to be placed on top of the composite structure where the weight of the device should be enough to detect any changes in structure (such as debonding).

3. Debonding Detection Experiment Subjected to Different Attachment Method

The roller device and the re-attachable device shown in Figure 1 were tested on two different composite structures to evaluate the performance of the two devices. In Figure 2, the two test specimens made for this study, Structure A and B. Structure A was created by attaching two glass fiber epoxy plates of size 150 mm × 150 mm with two different thicknesses of 0.2 mm and 0.4 mm are shown. For adhering to the composite plates, a commercial epoxy (quick-set Epoxy, Loctite, Düsseldorf, Germany) was used where the specimen was left for 48 h to ensure full curing. Only half of the area was adhered to search for differences in impedance signature as this would indicate that the proposed idea works. For both the roller device and re-attachable device, 10 impedance measurements were acquired from the bonded area and debonded area for Structure A. With the roller device, it was simply placed on top of the specimen for measuring impedance signature and moved to another random location for another measurement until 10 signatures were acquired for both bonded and debonded areas (resulting in 20 impedance signatures). For the re-attachable device, double-sided tape was used to achieve temporary attachment between the device and the composite plate to acquire 10 impedance signatures for both bonded and debonded areas. Then, this test was conducted identically for Structure B, where the top composite plate thickness was changed to a thicker plate of 0.4 mm to evaluate the performance of the roller device subjected to a different thickness.

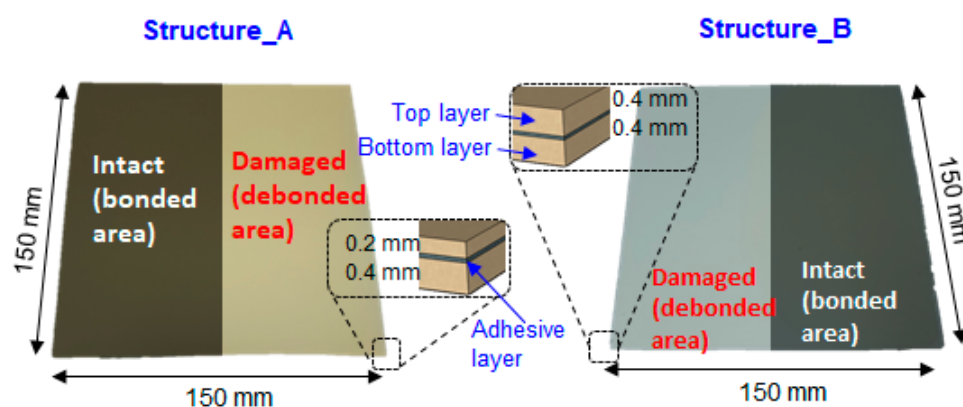


Figure 2. Composite structure specimens created for this study.

4. Results and Discussion

4.1. Experimental Results and Visual Analysis of Both Temporary Attachment Devices

Figures 3 and 4 show all impedance signatures described in the previous section. Figure 3a,b represents the impedance signatures using the re-attachable device where the dark orange-colored lines and light orange colored lines represent debonded and bonded area signatures, respectively. Although variations in signatures can be seen, one can clearly identify the difference between the two groups of signatures. The first observation was that the signatures from the debonded area had higher impedance peak amplitudes compared to the bonded area signatures for both figures. For Figure 3a involving the test on Structure A, the heights of most of the signatures for the debonded area were around 8 kOhms, where

the heights of the signatures for the bonded area were all less than 7 kOhms. Thus one can visually identify the difference between two different areas. Figure 3b shows a similar outcome using a thicker top plate of 0.4 mm where the heights of the impedance signatures from the bonded area had an amplitude of less than 7 kOhms as well. However, when the measurement was taken from the debonded area, the peaks generally shifted in the left direction (from around 35 kHz to 34 kHz), with most of the signatures resulting in over 7 kOhms. The reason for the increase in peak amplitudes when moving from bonded to debonded area is that with the debonded area, the top plate is free to vibrate in the thickness direction, resulting in higher amplitude. This is why with Figure 3b, the peak amplitudes for the debonded area were lower compared to Figure 3a since the thickness was twice the size, restricting vibration in the thickness direction.

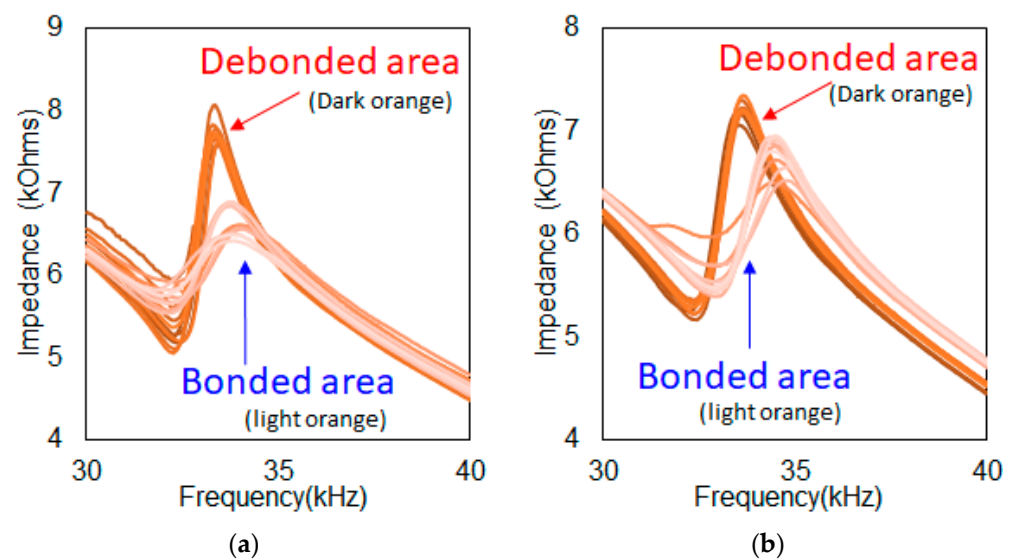


Figure 3. Impedance signatures measured from bonded and debonded areas using the re-attachable device for (a) 0.2 mm top plate; (b) 0.4 mm top plate.

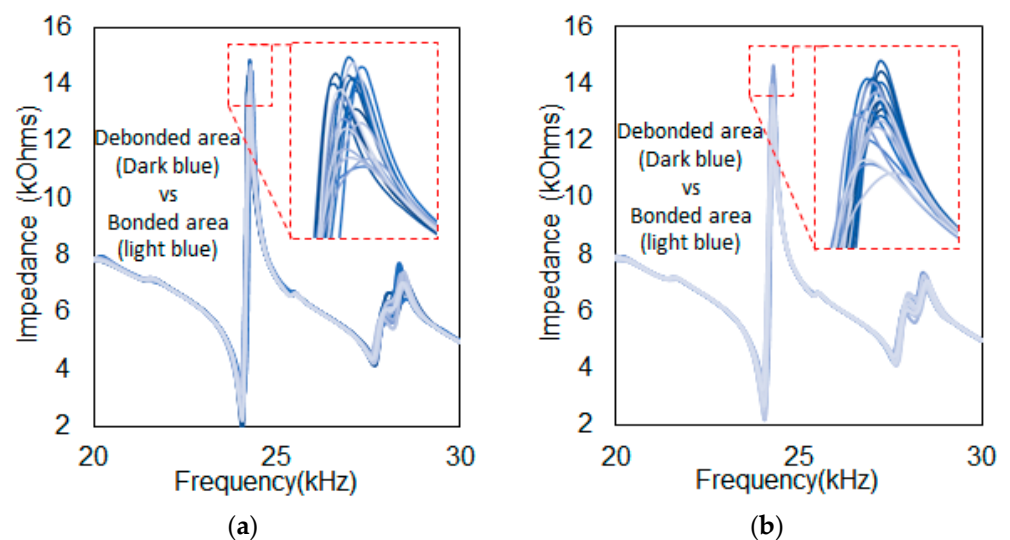


Figure 4. Impedance signatures measured from bonded and debonded areas using the roller PZT device for (a) 0.2 mm top plate; (b) 0.4 mm top plate.

Figure 4a,b represents impedance signatures using the roller device where the dark blue colored lines and light blue colored lines represent debonded and bonded area signatures, respectively. For both figures, signature variations were hardly noticeable by visual, and even with the zoom in at 24 kHz, it was very difficult to distinguish the difference between signatures from bonded and debonded areas. With the zoom-in, the variations in signatures existed, but one could say that this variation was due to the replacement of the roller device. Since the EMI technique used a high-frequency range over 20 kHz, replacing the roller device randomly onto another location can cause the signature to change, as shown in the figure. With the resonance peaks located at around 28 kHz, more variations in the signatures can be visually identified for Figure 4a when compared to Figure 4b. This result was quite similar to Figure 3, where the difference (the resonance peak difference between bonded and debonded area) was larger for Structure_A compared to Structure_B due to a thinner top plate of 0.2 mm. Comparing both Figures 3 and 4, it was clear that using the re-attachable device (Figure 3) can clearly distinguish between bonded and debonded areas. However, with the newly proposed idea of roller device, uncertainty remained as signature variations seemed to be random when zoomed in closely at the resonance peak of 24 kHz. Thus, further analysis is required to confirm the possibility of using the roller device for detecting defects in composite structures.

4.2. Statistical Analysis on Acquired Impedance Signatures

In the previous section, the acquired impedance signatures were visually analyzed to roughly investigate how the impedance signatures varied subjected to different areas and PZT attached devices. In this section, a statistical method known as the root mean square deviation (RMSD) after averaging the impedance signatures was used to quantify the size of the difference for impedance signatures. The RMSD metric was used to analyze the EMI technique in general, as it has been found to be effective in identifying damage. Here, Z_i^o and Z_i represent the signatures before and after damage, respectively. The variable N in the equation represents the number of the impedance signature:

$$\text{RMSD} = \sqrt{\sum_N [\text{Re}(Z_i) - \text{Re}(Z_i^o)]^2 / \sum_N [\text{Re}(Z_i^o)]^2} \quad (2)$$

Figure 5a,b shows the averaged impedance signatures for Figures 3 and 4, respectively. The 10 impedance signatures were averaged to create each line shown in the figure. For Figure 5a, the clear difference is seen between impedance signatures where the resonance peak increased from 6.5 kOhms (labeled '02_bo') to 7.6 kOhms (labeled '02_de') when moving from bonded area to debonded area. Here, a RMSD of 5.75% was calculated. Next, with the thicker top plate, the resonance peak increased from 6.6 kOhms (labeled '04_bo') to 7.2 kOhms (labeled '04_de') when moving from bonded area to debonded area. Here, a RMSD of 7.51% was calculated. Next, with Figure 5b, since there was a very small difference between the impedance signatures, the graph was zoomed-in between 24.1 kHz and 24.5 kHz to visualize the difference in impedance signatures. With the figure, there is a clear difference between the bonded and debonded areas where the resonance peak increased from 12 kOhms (labeled '02_bo') to 13.5 kOhms (labeled '02_de') when moving from bonded area to debonded area. Here, a RMSD of 2.47% was calculated. Next, with the thicker top plate, the resonance peak increased with a similar height from 12 kOhms (labeled '04_bo') to 13.5 kOhms (labeled '04_de'). Here, a RMSD of 2.68% was calculated. Comparing both RMSD values, similar experimental values showed that the thickness did not significantly affect the outcome. However, with the thicker plate of 0.4 mm, we can see that the resonance frequency was higher (right shift) compared to using a top plate of 0.2 mm. This promising outcome shows the possibility of using the proposed roller device for detecting debonding of composite plates.

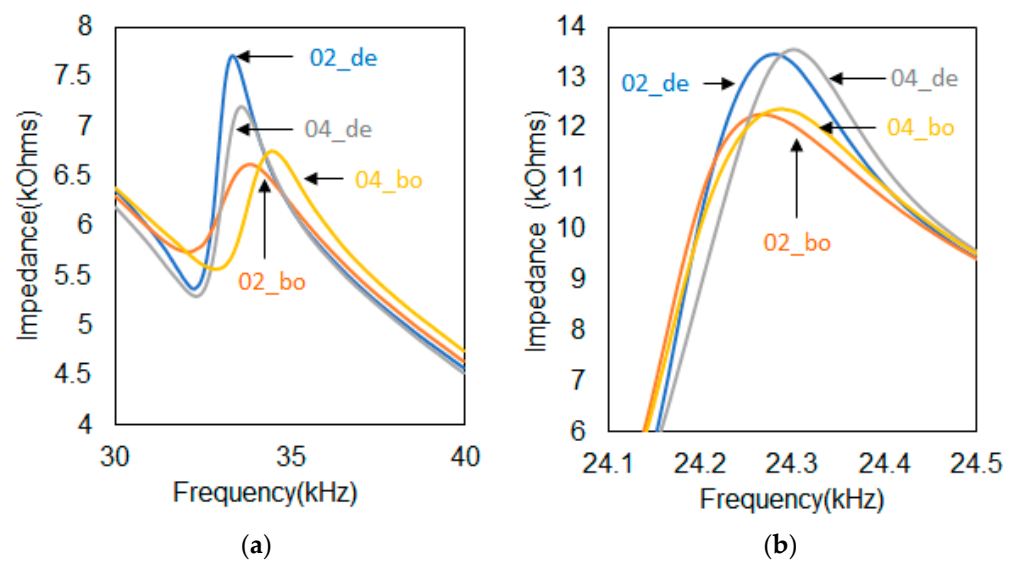


Figure 5. Averaged impedance signature signatures from (a) Figure 3; (b) Figure 4.

5. Conclusions

In this study, a new method of conducting the EMI technique was proposed and tested to evaluate its possibility for detecting debonding of composite structures. The idea of using a roller device by attaching a PZT transducer was experimented with on a glass fiber epoxy plate with two different thicknesses. The results were compared to another temporary attachment method to evaluate its performance, and the results showed that the newly proposed idea could detect debonding of composite plates. For the actual experiment, two composite structures were created using 150 mm squares with different thicknesses of 0.2 mm and 0.4 mm. With each composite structure, half of the area was adhered, using a commercial adhesive, where the newly proposed roller PZT device was used to measure impedance signatures on the bonded and debonded areas. Ten impedance signatures were randomly measured at each area where this was analyzed using a statistical metric known as root mean square deviation (RMSD). Here, the re-attachable device that was created in a previous study was compared to the newly proposed roller PZT device in this study. With the roller PZT device, the signature variations were very small, and it was virtually impossible to visualize the difference between the bonded and debonded area. However, when the impedance signatures were averaged and zoomed in to take a look at the signature closely, the results were promising, as the RMSD values of 2.47% and 2.68% were calculated when comparing the averaged impedance signatures from the bonded and debonded areas. Although that the thickness of the top composite plate did not significantly affect the RMSD values, one can see that the resonance peak increased when moving from the bonded to debonded area as the top plate was free to vibrate, allowing resonance with higher amplitude. Thus, using this fact, the roller PZT device could detect debonding of composite structures as the defect areas would result in higher resonance peaks. In addition, since the roller device can easily travel over any surface, the proposed idea could also be made into a robot device with wheels to develop a system that can automatically detect structural damage.

Author Contributions: W.S.N. was responsible for conceptualization and methodology of the work; D.-W.S. and K.-S.J. carried out the investigation and conducted the experiments; H.-J.K. and Y.-S.K. participated in writing the manuscript and analyzing the data. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Department of Structural Engineering Research, Korea Institute of Civil Engineering and Building Technology (KICT), project number 20210097.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Noman, M.T.; Wiener, J.; Saskova, J.; Ashraf, M.A.; Vikova, M.; Jamshaid, H.; Kejzlar, P. In-situ development of highly photocatalytic multifunctional nanocomposites by ultrasonic acoustic method. *Ultrason. Sonochem.* **2018**, *40*, 41–56. [[CrossRef](#)] [[PubMed](#)]
2. Scott, I.G.; Scala, C.M. A review of non-destructive testing of composite materials. *NDT Int.* **1982**, *15*, 75–86. [[CrossRef](#)]
3. De Goeje, M.P.; Wapenaar, K.E.D. Non-destructive inspection of carbon fibre-reinforced plastics using eddy current methods. *Composites* **1992**, *23*, 147–157. [[CrossRef](#)]
4. Aymerich, F.; Meili, S. Ultrasonic evaluation of matrix damage in impacted composite laminates. *Compos. Part B Eng.* **2000**, *31*, 1–6. [[CrossRef](#)]
5. Mahmood, A.; Noman, M.T.; Pechočiaková, M.; Amor, N.; Petrů, M.; Abdelkader, M.; Hassan, S.Z.U. Geopolymers and Fiber-Reinforced Concrete Composites in Civil Engineering. *Polymers* **2021**, *13*, 2099. [[CrossRef](#)] [[PubMed](#)]
6. Dos Santo, J.A.; Lopes, H.M.R.; Vaz, M.; Soares, C.M.; Soares, C.M.; De Freitas, M.J.M. Damage localization in laminated composite plates using mode shapes measured by pulsed TV holography. *Compos. Struct.* **2006**, *76*, 272–281. [[CrossRef](#)]
7. Avdelidis, N.P.; Moropoulou, A. Applications of infrared thermography for the investigation of historic structures. *J. Cult. Herit.* **2004**, *5*, 119–127. [[CrossRef](#)]
8. Wu, D.; Busse, G. Lock-in thermography for nondestructive evaluation of materials. *Revue générale de thermique* **1998**, *37*, 693–703. [[CrossRef](#)]
9. Liang, Y.; Feng, Q.; Li, D.; Cai, S. Loosening Monitoring of a Threaded Pipe Connection Using the Electro-Mechanical Impedance Technique—Experimental and Numerical Studies. *Sensors* **2018**, *18*, 3699. [[CrossRef](#)] [[PubMed](#)]
10. Zhang, J.; Xu, J.; Guan, W.; Du, G. Damage Detection of Concrete-Filled Square Steel Tube (CFSST) Column Joints under Cyclic Loading Using Piezoceramic Transducers. *Sensors* **2018**, *18*, 3266. [[CrossRef](#)] [[PubMed](#)]
11. Na, W.S. A portable bolt-loosening detection system with piezoelectric-based nondestructive method and artificial neural networks. *Struct. Health Monit.* **2021**, 14759217211008619. [[CrossRef](#)]
12. Le, T.C.; Phan, T.T.V.; Nguyen, T.H.; Ho, D.D.; Huynh, T.C. A Low-Cost Prestress Monitoring Method for Post-Tensioned RC Beam Using Piezoelectric-Based Smart Strand. *Buildings* **2021**, *11*, 431. [[CrossRef](#)]
13. Na, W.S. Low cost technique for detecting adhesive debonding damage of glass epoxy composite plate using an impedance based non-destructive testing method. *Compos. Struct.* **2018**, *189*, 99–106. [[CrossRef](#)]
14. Liang, C.; Sun, F.P.; Rogers, C.A. Coupled electro-mechanical analysis of adaptive material systems-determination of the actuator power consumption and system energy transfer. *J. Intell. Mat. Syst. Str.* **1997**, *8*, 335–343. [[CrossRef](#)]