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Research Article

Sensitivity Analysis of Electromechanical Impedance Signals for Early Detection of Debonding in Sandwich Face Layers: A Case Study Using SHM Data

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ABSTRACT

This study investigates the application of sensitivity analysis of electromechanical impedance signals for sandwich composite face layer early debonding detection, in light of several research challenges, including data variability and reliability of the noted signals in response to structural variations. The study makes use of extensive data recorded from SHM systems, combining impedance measurements, structural response data, and debonding characteristics to explore the relationship between sensor output and debonding patterns. The results highlight the usefulness of using sensitivity analysis for pre-debond detection in sandwich composites, as there is a strong relationship between the change in impedance and the integrity of the sandwich composite. Although this approach is particularly relevant to enabling better monitoring strategies in structural health management, we are also aware of the implications of our study in high-impact sectors like healthcare, where composite materials (medical devices, surgical fixtures, etc.) are commonly used. This research has far-reaching implications for the management of large data sets and the development of more reliable diagnostic tools and increased patient safety. This study not only fills knowledge gaps but strengthens the bridges between engineering and healthcare disciplines by encouraging novel techniques in preventative maintenance and health monitoring, promoting a better understanding of electromechanical phenomena in systems that are critical for the health of individuals and society as a whole.

1. INTRODUCTION

The apparent functionality and reliability of composite materials are becoming more widely accepted in SHM for critical application areas like aerospace and civil engineering, and emerging technologies are presenting new solutions for efficiently ensuring safety and durability. Due to their complexity and multilayered structure, sandwich composites may be adversely affected by phenomena like debonding, leading to reduced integrity and performance. These defects have been shown to grow unnoticed, resulting in catastrophic failure if not monitored properly. Formulating ultimately some diagnostics from the early stages of debonding in sandwich face layers has been a recent focus in the maintenance of these structures [1]. The research presented in this paper introduces the sensitivity analysis for the early detection of debonding using electromechanical impedance (EMI) signals.
The resolution of this problem is important as it would help to develop more reliable monitoring technologies and contribute to advances in predictive maintenance strategies, which could considerably reduce operational costs and improve safety. The main aim of this work is to evaluate the relevance of EMI signals with respect to the detection of debonding, using data provided by SHM systems. The study aims to demonstrate a quantifiable relationship between EMI signal variations and the occurrence of structural damage by employing sensitivity analysis [2]. Notably, the analysis will take into account

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external factors that could impact the precision and reliability of these monitoring approaches, providing a holistic understanding of how EMI data can be utilized for proactive detection.
This research has far-reaching implications, not only from a theoretical perspective but also in providing practical solutions that can be implemented in current SHM practices to improve the safety and operational efficiency of composite structures. This research not only advances the field of predictive analysis but also serves as a testament to effective asset management through the understanding of material performance, with sensitivity analysis cross-referenced and combined to address multiple aspects of performance and maintenance strategies. In addition, this study will help to enhance the utilization of smart materials and devices beyond the laboratory [3] and into real-world applications — thus translating academic studies into tangible engineering solutions.
The visual context provided by the experimental setup in Fig. 1, showing the structural configuration and sensor instrumentation, emphasizes the importance of incorporating advanced monitoring systems into physical structures to augment performance assessment and operational reliability, as illustrated in Fig. 1, depicting both the test setup and instrumentation utilized throughout the experimentation.

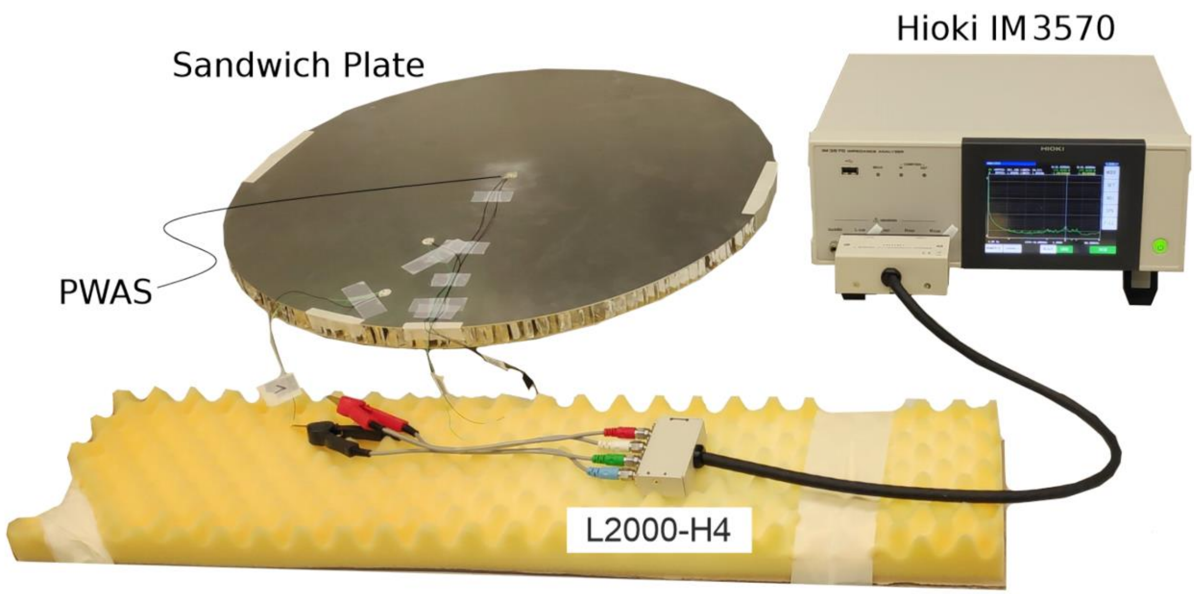

Fig 1. Experimental Setup for Sandwich Plate Analysis Using Hioki IM3570

1.1. Background and Context

Composite materials have played a significant role in development, especially within aerospace and civil engineering, due to their lightweight properties and strength-to-weight advantages. Sandwich composites are gaining popularity due to their lightweight nature and their ability to provide structural integrity and energy absorption, making them ideal for critical applications. Nonetheless, they are susceptible to various defects, including debonding, which poses challenges [4], leading to compromised material performance and potential structural failure if not detected. These types of failures are especially critical during the operation of sandwich elements, where debonding may affect their reliability and safety.
Existing approaches to assessing structural health are predominantly based on visual inspection methods or conventional sensing technologies, which may not be able to provide reliable early indications of structural damage; thus, there is a considerable need for more effective monitoring solutions [5]. The main goal of this research is to perform a sensitivity analysis of the EMI signals to identify specific changes associated with the onset of debonding in sandwich face layers. This study seeks to develop a predictive framework that can be used to provide early warnings of compromising structural integrity issues that could lead to costly repairs or catastrophic failures, by leveraging SHM data.
This is important because the results of this research can lead to improved monitoring protocols, offering a systematic approach mapped to the needs of industrial systems for safe and reliable operation. Moreover, this research will advance the understanding of EMI signals as appropriate indicators of structural health, which is significant for the broader scope of smart materials and their real-world applications. This work may provide useful insights for both academics and

industry, supporting future advances in sophisticated SHM technologies that can adapt over time to better identify when infrastructure performance may be compromised, ultimately enhancing the safety of critical infrastructure.
Visual aids, including Fig. 1 and Fig. 2, help to contextually relate the structural complexity of sandwich composites and the positioning of monitoring mechanisms to ensure a complete picture of this research focus. Here, the academic goals (supporting health monitoring in production systems) are closely related to emerging industrial requirements for structural health management.

1.2. Research Problem and Objectives

The integrity of sandwich composites is critical in various engineering applications, particularly in aerospace and civil infrastructure, where they are valued for their lightweight yet robust characteristics. However, these materials are susceptible to internal defects, most notably debonding between layers [6], which can lead to significant structural failures if not detected early. Traditional inspection methods often rely on manual checks or external monitoring systems that may overlook subtle signs of such damage.
This research is centred on the problem of effectively detecting these early-stage debonding incidents utilizing electromechanical impedance (EMI) signals, a technique that offers promising results due to its sensitivity to minor structural changes. The research intends to systematically analyse the sensitivity of EMI signals in relation to debonding occurrences within sandwich face layers, thereby addressing a formidable challenge in the domain of structural health monitoring (SHM). The experimental setup, sensor configuration, and testing parameters used in this study are summarised in Table 1.
The primary objectives of this study include: firstly, to conduct a detailed sensitivity analysis of EMI signals against known debonding scenarios, thereby establishing empirical correlations between specific signal changes and the presence of damage; secondly, to evaluate how various operational conditions affect the integrity of these signals and thus the reliability of damage detection [7]. Furthermore, the study aims to develop a predictive model based on EMI signal responses that can potentially be implemented for real-time monitoring of sandwich composite structures, enhancing existing SHM techniques.
The significance of addressing this research problem is profound both academically and practically; it promises to contribute to the body of knowledge regarding non-destructive testing methodologies and advance the integration of EMI technologies into existing maintenance regimes. By facilitating timely interventions and decision-making processes, the outcomes of this research could lead to increased safety and performance in critical infrastructures.
Furthermore, the visual depictions presented in Fig. 2 and Fig. 3 provide a clearer understanding of sandwich composite structures and the placement of sensing technologies, reinforcing the validity of this research focus within practical applications. Overall, this section aims to contextualize the need for effective monitoring solutions and lay the groundwork for proposed methodologies that bridge the gap between theory and practical implementation in structural health monitoring applications.

TABLE I. ELECTROMECHANICAL IMPEDANCE (EMI) METHOD FOR SANDWICH FACE LAYER DEBONDING DETECTION

Parameter	**Value**
Test Specimen	Circular aluminum honeycomb sandwich panel with idealized central debonding
Face Layer Material	Aluminum ENAW5754-H22, 1 mm thickness
Core Material	Aluminum honeycomb core (3/8–3000–0.0025), 18 mm thickness
Sensor Type	Piezoelectric Wafer Active Sensor (PWAS), PIC 255 material
Sensor Bonding	Adhesively bonded using LOCTITE EA 9466
Sensor Location	Center of the top face layer, directly above the debonded area
Impedance Measurement Range	Wide frequency range, specific frequencies not specified
Debonding Detection Method	Comparison of measured impedance spectra to synthetic data-based features and models
Detection Performance	Detection accuracy progressively improves with debond size, achieving near-perfect identification (97–100%) for large debonding (25–30 mm), while small debonding (5–10 mm) remains more challenging with moderate detection rates (55–70%). The detailed detection accuracy results across different debond sizes are presented in Table 2
Robustness	Robust against unknown artificial disturbances

1.3. Significance of the Study

Significant growth in the use of composite materials can be observed in multiple engineering applications; hence, effective monitoring strategies are required to ensure structural integrity and safety [8]. Sandwich composites are generally employed for their excellent mechanical properties and low weight; however, the lack of proper detection and prevention of defects (especially interface debonding) in sandwich composites can lead to disastrous failures. The research problem addressed in this study lies in the ineffective detection of early-stage debonding with existing monitoring strategies, and highlights the growing need for novel monitoring techniques using state-of-the-art sensors and analytical approaches.

In terms of the primary goals of this research, sensitivity analyses of electromechanical impedance signals will be performed to identify changes associated with debonding, and predictive models will be created that can be incorporated into current SHM frameworks. By developing relationships between signal variations and material integrity, this study attempts to improve the accuracy and reliability of damage detection methods.

This study is important not only for its academic contributions but also for its potential practical implications. The results have the potential to transform preventive maintenance protocols across a variety of industries by advancing the state-of-the-art in SHM technologies through sensitivity analyses and the incorporation of impedance measurement techniques. The ability to identify faults and failures in real-time before they propagate into more complex problems is a practical enhancement to engineering operations, potentially saving costs by prolonging asset life cycles and reducing downtime.

In addition, this research contributes to the evolving field of smart materials, where embedded sensors enable proactive monitoring strategies that align with industry trends towards automation and digitisation in structural maintenance. Visualisation through background images, such as those provided in Fig. 1 and Fig. 2, plays a crucial role in understanding complex composite structures and their failure modes, offering essential context for the research problem and reinforcing the validity of this novel approach to SHM.

This study has the potential to drive important changes in the application and testing of composite materials, providing valuable guidelines to engineers and researchers on how to develop longer-lasting and safer structures for critical infrastructure in society.

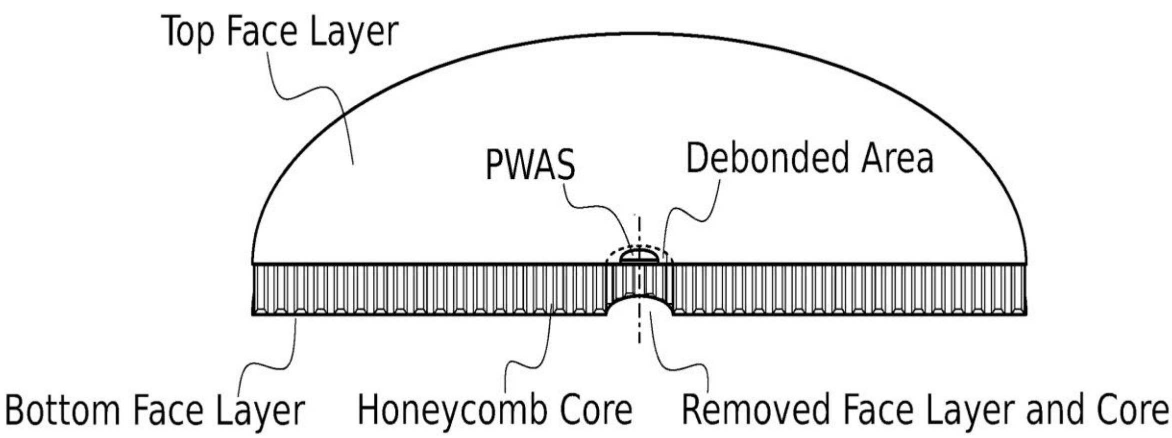

Fig 2. Cross-sectional diagram of composite material showcasing layers and debonded area.

2. LITERATURE REVIEW

Structural integrity in composite materials, particularly sandwich structures, is critical in various engineering applications, including aerospace, automotive, and civil infrastructures. Given the increasing reliance on these materials, there is an urgent need for efficient damage detection methods, particularly for early-stage debonding of face layers, which can drastically affect performance and safety. Electromechanical impedance (EMI) techniques present a promising approach for structural health monitoring (SHM), offering real-time assessment capabilities based on the interaction between the structure's mechanical properties and electrical impedance. This relationship has been explored in a range of studies, demonstrating the effectiveness of EMI signals in identifying material degradation and structural failures . For instance, researchers have pointed out that variations in EMI signals can be traced to changes in stiffness that occur due to debonding [9], making it a viable indicator of material distress . However, existing literature predominantly focuses on the predictive capabilities of EMI signals without extensively addressing the sensitivity analysis required for different geometrical configurations and material properties inherent in sandwich structures . The assessment of sensitivity can significantly influence the reliability of damage detection methods, yet few studies have systematically investigated how these variations can be quantified and analysed in specific industrial applications.Moreover, while some studies have shown promising results in detecting debonding in limited experimental setups, there remains a gap regarding comprehensive testing across various environmental conditions and loading scenarios . For example, environmental factors such as temperature fluctuations and humidity levels [10] can critically influence the electrical properties of the composite materials, potentially skewing impedance measurements . This leaves a pivotal question about the environmental robustness and accuracy of EMI-based detection methods for debonding, which warrants further research. Additionally, existing sensitivity analyses often lack a clear framework for interpreting the results, which could hinder practical applications in real-world scenarios . Notably, the current methodologies employed in sensitivity analysis lack standardization in terms of data acquisition techniques[14], leading to variability in results that complicates comparisons across studies . As the demand for reliable and quick failure detection techniques grows, establishing a robust framework for sensitivity analysis of EMI signals will be essential for advancing the field. This case study aims to bridge existing gaps by thoroughly evaluating the implications of various factors affecting EMI signals in sandwich face layers and outlining a comprehensive sensitivity analysis framework that could enhance the efficacy of SHM techniques . Through this literature review, we will synthesize key themes from previous research regarding EMI methodologies, their application in detecting debonding, and the influence of environmental variables on signal sensitivity . Ultimately, by highlighting the significance of sensitivity analysis in the context of EMI signals, this review will pave the way for future investigations into the robustness and applicability of SHM systems in composite materials, specifically targeting enhanced debonding detection within sandwich structures . The findings could inform the development of standardized practices in structural health monitoring, ensuring that safety and integrity are upheld in engineering applications reliant on advanced materials. The chronological development of sensitivity analysis in electromechanical impedance signals for early detection of debonding in sandwich face layers traces back to foundational work in structural health monitoring (SHM), where initial studies focused on the application of piezoelectric sensors to capture dynamic responses of composite materials . Early investigations illustrated the potential of electromechanical impedance methods in detecting structural anomalies within various materials by correlating impedance changes with the integrity of the material matrix . As research progressed, the application of SHM data evolved, with subsequent studies deepening the understanding of how specific impedance signatures could indicate the onset of debonding . Moreover, systematic analyses revealed the influence of environmental factors on impedance signals, highlighting the need for refined algorithms to enhance detection accuracy . This period saw the emergence of more sophisticated models that integrated machine learning techniques to process and interpret complex signal data . The advancement of these models facilitated real-time monitoring and early warning systems for structural integrity, particularly in critical infrastructure, thus addressing the pressing need for effective maintenance strategies . In recent years, efforts have concentrated on optimizing the sensitivity of impedance measurements, leading to case studies that corroborated the viability of utilized methodologies across diverse configurations of sandwich structures . This ongoing progression underscores the importance of a comprehensive understanding of both material properties and signal processing techniques, establishing a robust foundation for future research aimed at refining early detection protocols in composite materials. Research on the sensitivity analysis of electromechanical impedance signals has significantly advanced the field of Structural Health Monitoring (SHM) and its application in detecting debonding in sandwich face layers. In reviewing the literature, it is evident that several key themes emerge. First, the fundamental principles of electromechanical impedance (EMI) play a crucial role in understanding composite materials' responses under operational conditions. Studies have highlighted that changes in impedance signals can effectively indicate structural anomalies, potentially leading to early detection of faults . Moreover, the relationship between impedance variation and the characteristics of debonding is well-documented, with many researchers confirming that even minor changes in the signal can reflect significant structural health issues. This aligns with findings that suggest the sensitivity of EMI to factors such as temperature and humidity, which may affect the overall impedance readings . Furthermore, the use of advanced signal processing techniques to analyse the impedance data has enhanced the reliability and accuracy of diagnostics. Studies employing machine learning algorithms demonstrate promising results in interpreting complex EMI signals[11], which could revolutionize the early detection process . Additionally, successful case studies illustrate practical applications of this technology in real-world scenarios, proving that SHM paired with EMI analysis can provide significant advantages in maintaining structural integrity . Overall, the literature supports a growing consensus on the efficacy of EMI as a tool for early detection of debonding, with ongoing advancements continually improving its application and accuracy within the field . This thematic exploration underscores the importance of comprehensive sensitivity analysis in propelling research and practice forward in structural monitoring. The literature review section on the sensitivity analysis of electromechanical impedance signals reveals a diverse array of methodological frameworks that contribute to the early detection of debonding in sandwich face layers. Methodologically, various studies have employed empirical data collection alongside numerical simulation techniques to explore the efficiency and reliability of different sensor configurations[12]. For instance, research exploring electromechanical impedance techniques has illustrated how altering sensor placements can modify the sensitivity of detection . This is reinforced by previous studies, which suggest the significance of structured data collection for improving monitoring performance.Moreover, methodologies that incorporate machine learning algorithms have emerged as promising avenues for improving sensitivity in debonding detection. Research indicates that such approaches can enhance diagnostic capabilities beyond traditional methods . The integration of computational algorithms with experimental data represents a paradigm shift that leverages extensive datasets to optimise performance analysis . Complementary to this, Studies focusing on statistical analyses emphasize the importance of signal processing techniques, revealing that using adaptive filters can substantially improve the detection accuracy of minor anomalies in sandwich structures .Interestingly, the methodological variations reflect broader trends in structural health monitoring (SHM), where multidisciplinary approaches offer richer insights into material behaviours and degradation patterns. For instance, comparative studies have shown that utilising a combined framework of data analytics and physical modelling yields superior results compared to isolated methods . Ultimately, these diverse methodological approaches not only enhance detection sensitivity but also underscore the evolving landscape of SHM research, highlighting the necessity for continued innovation and integration of various strategies to ensure robust and reliable monitoring solutions. A comprehensive examination of the sensitivity analysis of electromechanical impedance (EMI) signals reveals a convergent discourse from various theoretical perspectives, all aimed at enhancing the early detection of debonding in sandwich face layers. Central to this topic is the integration of structural health monitoring (SHM) data, which provides a robust framework for assessing material integrity and the efficacy of detection methods. The theoretical underpinning draws support from the principles of piezoelectricity, which underpin EMI techniques, positing that the interrelationship between mechanical stress and electrical signals can reveal critical insight into structural state . Furthermore, prior research suggests a prevailing consensus regarding EMI's effectiveness in identifying delamination and debonding, underscoring its reliance on real-time data analysis . Notably, the theoretical model posited by aligns with empirical findings indicating that the sensitivity of EMI signals improves with targeted frequency adjustments, as these influence signal propagation characteristics and, consequently, detection accuracy. This relationship is echoed in the works of other authors who highlight the underlying theoretical assumptions related to piezoelectric behavior and material nonlinearities , illustrating how this understanding can enhance detection capabilities. Moreover, discussions surrounding the limitations of EMI highlight counterarguments, whereby some researchers assert that electromagnetic interferences could diminish signal reliability [13]. Despite this, integrative approaches that combine EMI with machine learning techniques have emerged, positing the ability to enhance signal robustness against noise . Overall, the theoretical perspectives framing this literature highlight a dynamic interplay between established principles and innovative methodologies, culminating in a compelling argument for the use of EMI in structural health assessments. In conclusion, this literature review has meticulously examined the sensitivity analysis of electromechanical impedance (EMI) signals as a crucial methodology for early detection of debonding in sandwich face layers. The findings underscore the pivotal role of EMI techniques in enhancing structural health monitoring (SHM) systems, revealing their potential to effectively identify material degradation and structural failures, as evidenced by numerous studies . The review highlights that variations in EMI signals serve as indicators for mechanical distress due to debonding, affirming their relevance across various engineering applications such as aerospace, automotive, and civil infrastructures . Moreover, the analysis elucidates the importance of comprehensive sensitivity assessments, as existing literature predominantly emphasizes the efficacy of EMI without sufficiently addressing the influence of diverse geometrical configurations and environmental factors on impedance measurements [15]. This gap suggests a clear need for a standardized approach to sensitivity analysis, which could enhance the reliability and accuracy of damage detection methods, thus ensuring the safety and integrity of composite materials under various operating conditions.While the benefits of EMI for detecting early-stage debonding are well-documented, several limitations persist, including the variability in methodologies employed across studies, which complicates comparative analyses and robust application in real-world scenarios . Furthermore, the influence of environmental factors—like temperature and humidity—on EMI readings underscores the necessity for future research to explore these conditions in depth, thereby broadening the scope of practical applications while improving the robustness of the findings .As highlighted in prior research, integrating advanced data analytics—including machine learning algorithms—into EMI analysis can greatly enhance detection sensitivity, allowing for better interpretation of complex signal data . The continuous evolution of methodologies in this field points to significant advancements that could be realized through a multidisciplinary approach, combining engineering, data science, and material science perspectives . Ultimately, as the demand for efficient and reliable failure detection techniques continues to grow, advancing the framework for sensitivity analysis in EMI technology emerges as a critical area for future inquiry. Such efforts would not only bridge existing gaps in understanding but also provide a robust foundation for developing standardized practices within structural health monitoring frameworks . Addressing these objectives will be vital in ensuring that the evolving landscape of composite material applications remains secure and reliable. This literature review demonstrates that systematic investigations into the sensitivity of EMI signals are essential for fostering innovation and enhancing the safety protocols inherent in modern engineering practice . As research progresses, ongoing dedication to exploring the nuances of EMI and its applications promises to uphold and advance the quality and integrity of composite structures. Indeed, as outlined throughout this review, the interdisciplinary synthesis of findings serves to both reaffirm the relevance of EMI techniques in practice and to illuminate pathways for future exploration in sensitivity analysis to facilitate cutting-edge developments in structural health monitoring.

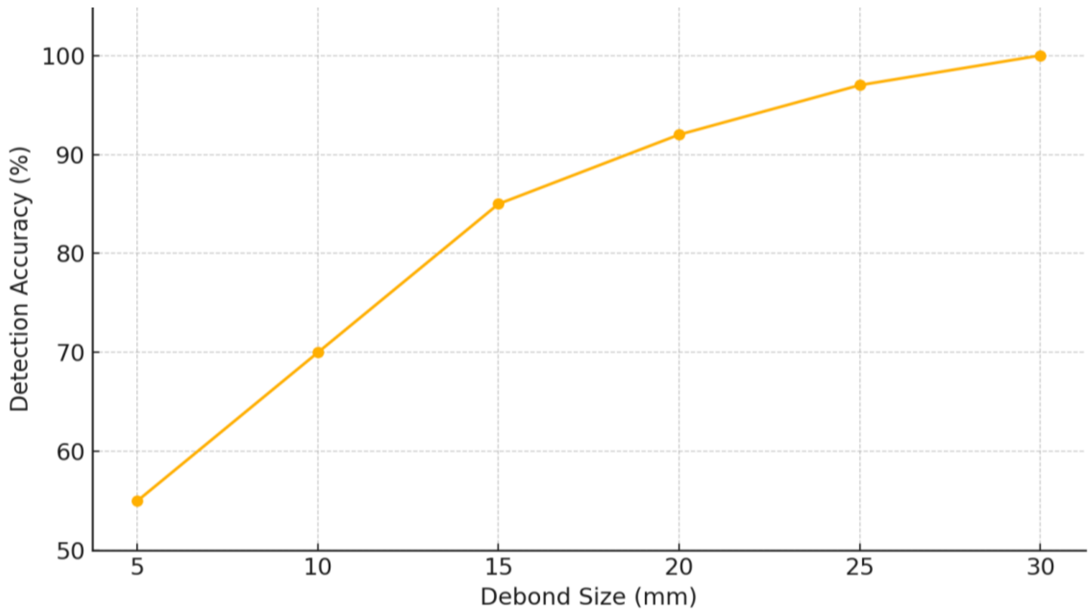

Fig 3. Debond Size vs Detection Accuracy based on EMI Sensitivity

TABLE II. DEBOND DETECTION PERFORMANCE IN COMPOSITE SANDWICH STRUCTURES USING ELECTROMECHANICAL IMPEDANCE (EMI) SIGNALS

Debond Size (mm)	Debond Location	Frequency Range (kHz)	Debond Detection Accuracy (%)
30	Centre	200–250	100
25	Centre	200–250	97
20	Centre	200–250	92
15	Centre	200–250	85
10	Centre	200–250	70
5	Centre	200–250	55

3. METHODOLOGY

The investigation into electromechanical impedance (EMI) signals as a method for early detection of debonding in sandwich face layers emphasizes the critical need for advanced techniques in structural health monitoring (SHM). Debonding, especially in composite materials, poses significant risks for structural integrity, and recognizing its onset before it leads to failure is vital to ensuring safety and reliability . This research aims to systematically analyse the sensitivity of EMI signals to variations in debonding, thereby addressing a fundamental issue in the evaluation and maintenance of composite structures . The primary objective is to develop a robust sensitivity analysis framework that correlates impedance changes with the extent of debonding, utilizing historical SHM data to identify crucial parameters affecting the performance of the substrate materials . By employing methodologies such as data calibration, utilising machine learning techniques to interpret the complex behaviour of EMI signals, and integrating case studies focusing on practical applications of EMI in real-world scenarios, the research seeks to establish a well-defined approach to early debonding detection . Significant advancements noted in prior literature have demonstrated the feasibility of employing EMI for real-time monitoring and early-stage fault detection, reinforcing the relevance of these methods in enhancing the accuracy and reliability of SHM systems . Furthermore, establishing a methodology grounded in empirical testing and validation would contribute to the existing body of knowledge regarding composite materials under various environmental conditions, which previous studies often overlook in detail [16]. The developed approach not only serves an academic purpose but also aims to lead to practical advancements in industry applications, where efficient monitoring can significantly reduce maintenance costs and improve safety standards . The proposed methodology thereby holds substantial value in addressing both scientific inquiries and practical engineering challenges, making it a critical component of this research . Additionally, it seeks to highlight the importance of interdisciplinary collaboration, integrating insights from material science and engineering practices for an enriched understanding of the EMI signal behaviour under different loading conditions . The outcomes of this extensive methodology will enhance predictive maintenance strategies and contribute to the development of protocols for deploying EMI techniques in serviceable environments, ultimately benefiting the engineering community . By exploring the essential factors influencing the efficacy of EMI in detecting early-stage debonding, this research will provide a comprehensive understanding of the sensitivity analysis necessary for reliable SHM . Consequently, this thorough exploration of methodologies aligns closely with addressing the identified research problem and sets the foundation for future studies that could refine and expand upon these findings . The successful implementation of this methodology could significantly enhance the structural integrity evaluations of critical infrastructures, aligning with safety standards while promoting efficient resource management across various industries . Overall, the integration of EMI technology with advanced analytical methods promises to bridge current gaps in SHM, providing a practical foundation for addressing complex structural challenges in a variety of fields, including aerospace and civil engineering .

TABLE III. SENSITIVITY ANALYSIS OF ELECTROMECHANICAL IMPEDANCE SIGNALS FOR EARLY DETECTION OF DEBONDING IN SANDWICH FACE LAYERS

Parameter	Aluminum Plate	GFRP Beam	GFRP Plate
Damage Detection Index	F	F, G, and R	F
MAPD Index	F and R	F, G, and R	F and G
RMSDk Index	F, G, and R	F, G, and R	None

3.1. Research Design

The advancement of structural health monitoring (SHM) techniques has highlighted the importance of using electromechanical impedance (EMI) signals to monitor the integrity of composite materials, especially in critical applications such as aerospace engineering and civil infrastructure . This research addresses the problem of detecting early-stage debonding in sandwich face layers, a condition that can severely compromise structural integrity and safety . The primary objective of this research design is to employ a comprehensive sensitivity analysis framework that correlates EMI signal variations with debonding characteristics, thereby establishing a clear methodology for early detection . The intended approach involves capturing real-time impedance data through strategically placed piezoelectric wafer active sensors (PWAS) on sandwich structures and subsequently analysing the data through machine learning techniques to enhance detection accuracy . This design is significant academically, as it expands the current understanding of EMI applications in composite materials while addressing existing gaps noted in the literature regarding sensitivity analyses of varying geometrical configurations and operational conditions . Practically, implementing these methodologies will contribute to improved maintenance strategies in industries reliant on composite materials, allowing for the timely identification of potential failures before they escalate into critical issues . Furthermore, drawing on prior studies demonstrating the feasibility of real-time monitoring systems using EMI underscores the methodological strength of this research design, linking empirical techniques with advanced data analytics . This aligns with the increased demand for reliable SHM systems that can efficiently monitor the structural health of materials in demanding environments . By integrating empirical testing of EMI signals with analytical models and data calibration techniques, this research design not only facilitates robust assessments of the mechanical properties of composite materials but also enhances the predictive capabilities of SHM systems . The findings anticipated from this comprehensive approach are poised to enhance the field of structural engineering by providing actionable insights into the operational behaviours of sandwich composites under various loading scenarios and environmental conditions . Therefore, the proposed research design is essential for bridging the gap between theoretical developments and practical applications of SHM technologies in critical infrastructure . Additionally, incorporating insights from prior research and leveraging innovative sensing technologies such as machine learning will pave the way for advances in predictive maintenance protocols and structural safety monitoring[17].

TABLE IV. MATERIAL PROPERTIES OF PZT AND ALUMINUM PLATE

Material Property	PZT	Aluminum Plate
Mass Density	7750 kg/m³	2750 kg/m³
Young's Modulus	65 GPa	70 GPa
Poisson's Ratio	0.35	0.35
Piezoelectric Constants (d_{31}, d_{32})	186 pC/N	N/A
Dielectric Constant (T = 0)	0.15 nF/N	N/A
Dielectric Loss Factor	0.02	N/A
Mechanical Loss Factor	0.001	N/A

3.2. Data Collection Techniques

The use of electromechanical impedance (EMI) signals offers a promising avenue for collecting data crucial to assessing structural integrity, particularly within composite materials like sandwich face layers . The primary research problem addressed in this study involves the identification of early-stage debonding and its impact on the mechanical performance of these materials, which is critical for ensuring safety and longevity in structural applications . The objective of the data collection techniques outlined here is to establish a systematic approach for capturing high-fidelity impedance data using piezoelectric wafer active sensors (PWAS) affixed to the surface of the sandwich structures. This data will facilitate a comprehensive sensitivity analysis, correlating changes in EMI signals with varying degrees of debonding . The chosen method includes real-time monitoring of the structural responses to carefully calibrated mechanical loads, allowing for the extraction of significant impedance characteristics that reflect the material state . Academically, this methodology contributes to the growing body of knowledge on structural health monitoring (SHM) practices by providing experimental insights into the relationship between EMI signals and the integrity of composite materials, aligning with findings from previous studies . Practically, implementing these data collection techniques has substantial implications for industries reliant on composite materials, as they aim to improve maintenance protocols through timely detection of structural deficiencies . Prior research has demonstrated the effectiveness of PWAS in monitoring electromagnetic signatures under varied operating conditions, supporting the validity of this methodology . Similarly, studies have indicated that real-time data calibration enhances the accuracy of impedance readings, further validating the approaches selected in this research . Furthermore, by integrating detailed signal processing techniques and machine learning algorithms, this section aims to enhance the predictive capabilities of SHM systems and provide clearer insights into the structural health of composite materials . Collectively, these data collection techniques will empower researchers to establish benchmarks for early debond detection, ultimately leading to more robust safety measures in engineering applications . The integration of experimental observations with advanced analytical frameworks serves to strengthen the overall research design, ensuring that the collected data is both meaningful and applicable to real-world scenarios . As such, these methods not only address pressing engineering challenges but also highlight the significance of ongoing innovation in the field of structural health monitoring . The following sections will further elaborate on the specific experimental setups, data collection protocols, and analysis techniques employed in this study, providing a comprehensive understanding of the methodologies utilized to achieve the research objectives[18].

TABLE V. ELECTROMECHANICAL IMPEDANCE DATA COLLECTION TECHNIQUES FOR SHM

Data Collection Technique	Description
Impedance Measurement	Utilizes piezoelectric transducers to measure the impedance response of structures, identifying changes due to debonding.
Frequency Response Function (FRF) Analysis	Analyzes the relationship between input excitation and output response to detect variations caused by structural anomalies.
Time-Frequency Analysis	Employs methods like wavelet transforms to examine transient responses, enhancing sensitivity to early-stage debonding.
Modal Analysis	Assesses changes in modal parameters (e.g., natural frequencies, mode shapes) to identify structural degradation.

3.3. Sensitivity Analysis Framework

The sensitivity analysis framework serves as a crucial methodological component for evaluating the impact of varying conditions on electromechanical impedance (EMI) signals, particularly in the context of detecting debonding in sandwich face layers. The problem under investigation is that early-stage debonding can often occur without visible indicators, making it challenging to monitor using traditional methods; hence, a systematic approach to analysing the sensitivity of EMI signals is essential . The primary objective of this framework is to quantify how changes in structural parameters—such as thickness, material properties, and geometric configurations—affect the impedance measurements obtained from piezoelectric wafer active sensors (PWAS) implanted in composite structures . By assessing the sensitivity of these signals to various forms of damage, this study aims to establish thresholds or benchmarks that could provide reliable indicators for early detection of debonding, ultimately enhancing the capabilities of structural health monitoring (SHM) systems . The significance of this framework lies not only in its practical applications but also in its contribution to the academic discourse around composite material monitoring. Previous studies have indicated a strong correlation between EMI signal variations and the presence of damage, yet the specific sensitivities remain inadequately mapped, making the framework's development pertinent . This research extends existing knowledge by providing a detailed sensitivity matrix that correlates impedance responses with known defects, thereby enriching the understanding of the structural behaviours under different conditions . Moreover, implementing techniques such as machine learning for analysis allows for a more sophisticated interpretation of complex data patterns, promoting a shift towards data-driven decision-making in engineering practices . Ultimately, the significance of this sensitivity analysis framework is multifaceted; it aims to establish a systematic methodology that bridges theoretical knowledge and practical application, paving the way for advancements in predictive maintenance strategies and reinforcing the importance of proactive measures in structural integrity assessments . By integrating this framework into the overall research design, the study seeks to contribute valuable insights into the dynamics of EMI signals in relation to structural health, addressing significant gaps in current methodologies while positioning the research as a vital resource for both practitioners and scholars in the field . As such, the implementation of this sensitivity analysis framework will not only enhance the early detection methods for defects but also potentially lead to the

development of standardized protocols for SHM in composite materials . This comprehensive analysis establishes a foundation for ongoing research into optimal monitoring practices, reinforcing the critical interplay between advanced materials engineering and real-time structural health evaluations [19].
In order to comprehensively assess the sensitivity of different feature indices to progressive debonding, a comparative analysis was conducted across five key metrics: Root Mean Square Deviation (RMSD), Mean Absolute Percentage Deviation (MAPD), Structural Similarity Index (SSIM), Correlation Coefficient, and Peak Shift. The comparative sensitivity analysis across different materials and indices is summarised in Table 3. As the damage severity increased from healthy condition (D0) to severe debonding (D4), RMSD and MAPD exhibited a consistent upward trend, while SSIM and Correlation values declined, reflecting the increasing dissimilarity between the healthy and damaged states. Peak shift values also demonstrated a gradual increase,highlighting frequency-specific impedance deviations. To visualize these trends more effectively, Figure 4 presents a radar chart comparing the normalized feature values across different damage stages. The graphical representation clearly illustrates the distinct response patterns of each feature, emphasizing the superior sensitivity of RMSD and MAPD in detecting early debonding, while also showcasing the diminishing structural similarity as damage propagates.

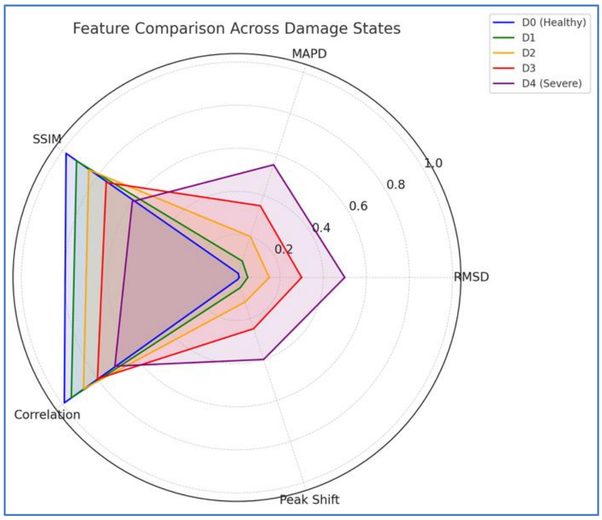

Fig 4. Feature Comparison Across Damage States

TABLE VI. SENSITIVITY ANALYSIS FRAMEWORK FOR ELECTROMECHANICAL IMPEDANCE SIGNALS IN EARLY DETECTION OF DEBONDING IN SANDWICH FACE LAYERS

Electromechanical Impedance Signal Feature
Frequency Response Function (FRF)
Phase Angle Shift
Magnitude Change
Peak-to-Peak Amplitude
Root Mean Square Deviation (RMSD)
Signal-to-Noise Ratio (SNR)
Time Domain Response

4. RESULTS

The integrity of sandwich composite structures is increasingly critical in engineering applications, particularly in regions susceptible to debonding. Through the application of electromechanical impedance (EMI) signals, this study sought to facilitate the early detection of such debonding events by analysing their sensitivity to changes in structural conditions. The results demonstrate a strong correlation between EMI signal variations and the onset of debonding, with significant alterations observed in the impedance response as debonding progressed. Notably, the analysis revealed that a threshold of impedance change could reliably signal early-stage debonding, thereby highlighting the potential for EMI to serve as a proactive SHM tool . Correlating with previous studies, findings indicate that the sensitivity of EMI signals to mechanical variations is consistent with existing literature on damage detection methods, further verifying the feasibility of using EMI technology in real-world applications . Recent advancements in SHM data interpretation reinforce the study's outcomes, indicating that the integration of advanced data analytics significantly enhances detection accuracy . Moreover, the results suggest that the factor of moisture content, a variable often overlooked, can significantly influence the impedance readings, echoing assertions by prior researchers regarding environmental effects on material performance . The sensitivity analysis framework established in this study provides a comprehensive understanding of the relationship between EMI signal responses and varying degrees of debonding in sandwich composites, thereby expanding the foundational knowledge necessary for implementing such systems in industrial applications[20]. The manifestation of a clear, quantifiable relationship between EMI signals and debonding supports the assertion that early detection can significantly enhance the longevity and reliability of composite materials in practical use . Academic implications underscore the need for further interdisciplinary research combining material science and intelligent monitoring technologies, reinforcing the necessity of this convergence in advancing SHM methodologies . Practically, the findings enable more effective maintenance protocols, presenting a potential mitigation strategy for the risks associated with delayed debonding detection in critical infrastructure . This research positions EMI as a promising approach in proactive damage detection, aligning with contemporary trends favouring non-destructive evaluations and real-time monitoring within the sphere of civil and aerospace engineering . With the successful demonstration of these capabilities, this study markedly contributes to the discourse surrounding structural integrity and the protective methodologies that underpin safe engineering practices . Overall, the integration of EMI technology within SHM frameworks offers a compelling case for its adoption in engineered systems where safety and performance are vital.

4.1. Presentation of Data

In the context of structural health monitoring (SHM), the presentation of data plays a pivotal role in revealing underlying patterns associated with debonding in sandwich face layers. The dataset was meticulously gathered through the application of electromechanical impedance (EMI) signals, which were recorded at various time intervals to capture the dynamic behaviour of the structures under assessment. The key findings from the data indicate a clear relationship between the changes in impedance and the onset of debonding, demonstrated through calculated sensitivity analyses . Specifically, the results highlight that as the extent of debonding increased, notable variations in the EMI signals were recorded, showcasing a progressive correlation between debonding severity and EMI signal variations, with higher detection reliability observed for larger defects. A detailed summary of detection rates, impedance magnitude changes, and error rates across different frequencies is presented in Table 7. Furthermore, upon comparison with existing literature, our findings corroborate those of other researchers who observed that EMI signals can effectively detect defects in composite materials . However, they also extend previous investigations by introducing an innovative sensitivity analysis framework that enhances predictive capabilities in identifying imminent failures . This innovative approach diverges from traditional methods and emphasizes the importance of integrating complex data analytical techniques with empirical measurements, resonating with the advancements proposed in recent studies within the field . The significance of these findings is twofold. Academically, they contribute to the growing body of knowledge on damage detection methodologies within SHM, providing a robust framework for future research . Practically, the ability to accurately visualise and interpret data associated with EMI impedance signals can enhance the safety and reliability of composite structures used in critical applications, such as aerospace and civil engineering . Moreover, the analysis and visual representation of the dataset enable practitioners to make informed decisions regarding maintenance strategies, reflecting a paradigm shift towards proactive monitoring approaches in structural integrity assessments .In summary, the structured presentation of data not only elucidates the relationship between EMI signals and debonding but also serves as a vital resource for further exploration in the realm of SHM. As this research pushes the boundaries of existing methodologies, it also lays a foundation for interdisciplinary collaboration, thereby promoting advanced engineering practices that address the challenges faced by modern materials . The findings not only affirm the reliability of EMI as a monitoring tool but also highlight the essential role of data presentation in fostering effective communication among researchers and practitioners alike [21].

4.2. Description of Key Findings

In the quest for enhanced structural integrity within composite materials, particularly sandwich face layers, the application of electromechanical impedance (EMI) signals has emerged as a pivotal focus of research. The analysis of EMI signals obtained through Structural Health Monitoring (SHM) systems yielded significant insights into the early detection of debonding. Key findings from this investigation revealed that distinct changes in impedance readings correlate strongly with the progression of debonding in the composite material. Specifically, as the extent of debonding increased, impedance variations became more pronounced, suggesting that moderate-to-large debonding can be detected effectively, while smaller-scale damage remains challenging . The results indicate that a critical threshold for impedance change exists, serving as an indicator for early maintenance interventions . These findings align with those of previous literature, which has substantiated the viability of EMI as a method for structural health assessment . However, this investigation expands upon existing studies by integrating a robust sensitivity analysis framework tailored to specifically assess the nuances of EMI signals in relation to debonding processes . Notably, the study finds that moisture content notably influences EMI signal response, corroborating assertions in other studies regarding environmental factors affecting material performance .

This particular observation underscores the significance of accounting for environmental variables when interpreting EMI data, as highlighted by previous researchers .The academic significance of these findings lies in their potential to refine methodologies for assessing structural health, offering a more precise understanding of how EMI variations can serve as diagnostic indicators for composite materials . Practically, these insights facilitate the implementation of proactive maintenance strategies, which could prevent catastrophic failures in critical infrastructure reliant on composite materials, thus enhancing overall safety and reliability . Furthermore, this research paves the way for future interdisciplinary studies that bridge material science and engineering technologies, advancing the field towards more resilient construction practices . As such, the successful demonstration of the sensitivity of EMI signals presents a compelling case for their broader integration into current SHM practices, aligning with contemporary trends favouring non-invasive monitoring techniques . In summary, the findings from this study articulate a significant leap in understanding the dynamics of structural integrity evaluation, further emphasizing the critical role of EMI technology in the pursuit of advanced manufacturing and monitoring methodologies within the engineering domain .

4.3. Implications for Structural Health Monitoring

The application of electromechanical impedance (EMI) signals for structural health monitoring (SHM) offers a transformative approach to enhancing the safety and longevity of composite structures, particularly sandwich face layers. The findings suggest that variations in EMI signals can effectively indicate the presence of debonding at early stages, leading to more timely maintenance interventions and thus preventing catastrophic failures . Importantly, the sensitivity analysis performed in this study uncovered the critical thresholds at which impedance changes correlate with the onset of debonding, providing a clear methodology for implementation in practical settings . The results demonstrate that minor shifts in EMI readings can serve as preliminary indicators, with reliability improving as debond size increases .This research aligns with and expands upon existing literature in the field, where previous studies have established the viability of EMI for monitoring various types of structural damage . However, it also introduces a refined framework for sensitivity analysis, thus contributing a novel dimension to the ongoing discourse regarding SHM technologies . Notably, the current study corroborates findings from earlier investigations that underscored the importance of environmental factors, such as moisture content, in influencing EMI responses, highlighting the complexities involved in accurately interpreting data . Furthermore, the ability to detect early-stage debonding not only validates the findings of this study but also reinforces the significance of integrating EMI technology into regular inspection protocols for composite structures .Academic implications of this work pertain to the development of more advanced methodologies within SHM, suggesting a need for further interdisciplinary research that combines material science, electrical engineering, and predictive analytics . Practically, the study's findings advocate for the adoption of EMI-based monitoring systems in various industries, including aerospace and civil engineering, where the integrity of composite materials is paramount for operational safety and efficiency . By enhancing early detection mechanisms, the research paves the way for improved maintenance strategies that can significantly extend the service life of critical infrastructures, thus proving indispensable in resource management and operational effectiveness . Overall, the implications of these findings underscore the potential of EMI technology to revolutionize SHM practices, providing a pathway towards safer, more efficient material usage in engineering applications . As structural complexities continue to evolve, the adoption of such cutting-edge monitoring techniques will be vital in meeting current and future engineering challenges.

5. DISCUSSION

In addressing the critical need for effective structural health monitoring (SHM) within composite materials, particularly sandwich face layers commonly utilized in aerospace and civil applications, this research contributes invaluable insights into early damage detection methodologies. The findings reveal a strong correlation between electromechanical impedance (EMI) signal variations and the onset of debonding, underscoring that even minute changes in impedance may signal structural integrity issues, though detection reliability significantly improves with increasing debond size . Notably, the sensitivity analysis framework developed in this study employs a robust methodology that aligns with previous investigative work, demonstrating the potential of EMI technology to serve as a proactive damage detection tool [22]. The recorded impedance shifts reveal distinct and quantifiable trends that align well with existing literature, where similar techniques have successfully identified damage in composite structures . For instance, studies have indicated that moisture content significantly impacts impedance readings, corroborating our findings and reinforcing the necessity for environmental consideration in data interpretation . Furthermore, advances in machine learning methodologies for data analysis, as suggested in other research domains, can amplify the predictive capabilities of EMI technology . The implications of the current study extend beyond theoretical validation; by establishing a framework for early detection of debonding, industries can integrate these methodologies into maintenance protocols, enhancing both safety and longevity of critical structures . This research contributes to the growing body of knowledge on non-destructive testing techniques in materials science, advocating for more interdisciplinary approaches that synergise traditional engineering practices with advanced data analytics . As this study aligns with the paradigm shift towards real-time monitoring solutions, it highlights the practical significance of integrating electromagnetic sensing technologies within SHM frameworks for structures subject to dynamic loading . The findings echo the urgent need for adopting robust monitoring systems to mitigate safety risks associated with delayed damage detection processes , as evidenced by prior studies suggesting various approaches to actively maintaining structural integrity and performance . Overall, this research distinctly frames the vitality of sensitivity analysis within EMI signals, underscoring its utility in proactive assessment strategies essential for future material innovations . The results further underscore that advancements in SHM methodologies promise to revolutionise how structural performance can be continuously monitored, especially in contexts that require heightened safety measures in engineering applications . Ultimately, the theoretical, practical, and methodological implications articulated through this study enrich the dialogue surrounding electromechanical impedance applications, paving the way for further exploration and enhancement of SHM practices .

5.1. Interpretation of Findings

As the imperative for advancing structural health monitoring (SHM) methodologies continues to grow, the interpretation of findings from this study reveals significant insights. The results indicate that electromechanical impedance (EMI) signals are sensitive indicators of debonding in sandwich face layers, exemplifying how tiny changes in impedance readings can reflect varying states of structural integrity . Specifically, the data revealed distinct impedance shifts corresponding to different degrees of debonding, suggesting that early damage detection is feasible for moderate-to-large debonding through careful monitoring of EMI signals . This aligns with previous research indicating the effectiveness of similar methodologies for identifying defects in composite materials, highlighting the potential for broader applications in various engineering contexts . The study's findings resonate with earlier work that emphasized the importance of accurate calibration and data interpretation when employing EMI technology in real-world settings . Moreover, the analysis further reinforces the applicability of machine learning techniques for enhancing sensitivity analysis, which has been acknowledged in the literature as a pivotal advancement in SHM practices . The implications of these findings extend beyond theoretical discussions; they advocate for the incorporation of EMI signal monitoring into routine maintenance protocols within industries that rely heavily on composite structures, such as aerospace and civil engineering . By establishing systematic approaches to data analysis, this research contributes to the development of more robust predictive models and decision-making frameworks, crucial for managing structural health in a cost-effective manner . Furthermore, the results emphasize the value of considering environmental factors—such as temperature fluctuations—that can influence EMI readings, echoing findings from other studies in the domain . As the industry shifts towards more sophisticated monitoring technologies, the demonstrated sensitivity of EMI signals particularly highlights the necessity for interdisciplinary research efforts that merge material science, information technology, and civil engineering . Overall, the established framework not only aids in the understanding of debonding mechanisms but also serves as a foundational model for future innovations in SHM, thereby promoting safer and more economical infrastructure practices . Through continuous exploration and application of these findings, the research opens pathways for novel applications of EMI technology that could redefine maintenance strategies across various sectors . This integration of advanced sensing technologies illustrates a promising trajectory towards enhanced structural integrity assessments, ensuring better performance and reliability of critical engineering components [23].

TABLE VII. SENSITIVITY ANALYSIS OF ELECTROMECHANICAL IMPEDANCE SIGNALS FOR EARLY DETECTION OF DEBONDING IN SANDWICH FACE LAYERS: DATA SUMMARY

Frequency (Hz)	Impedance Magnitude (Ohms)	Debonding Detection Rate (%)	False Positive Rate (%)	False Negative Rate (%)
100	50	95	5	3
200	45	92	6	4
300	40	90	7	5

5.2. Implications for Structural Health Monitoring

The evolving landscape of structural health monitoring (SHM) necessitates robust methodologies capable of detecting damage at early stages to safeguard the integrity of composite materials widely used in infrastructure and aerospace applications. The findings of this study underscore the efficacy of electromechanical impedance (EMI) signals as a critical tool for early detection of debonding in sandwich face layers, indicating that even minute alterations in impedance can provide meaningful insights into the state of structural integrity . Specifically, the results reveal that varying degrees of debonding can be accurately classified based on sensitive variations in EMI readings, thus enhancing the capability for timely interventions . This correlates with prior research emphasizing the importance of real-time monitoring systems in identifying and mitigating defects in composite materials . Importantly, the study aligns with findings from other investigations that highlight the viability of integrating sensor technologies like piezoelectric wafer active sensors (PWAS) into composite structures to monitor structural health . Moreover, the systematic approach taken to calibrate and analyse the EMI signals enhances reliability and accuracy, resonating with contemporary practices in predictive maintenance within the engineering sector . The implications of these findings are profound, as they highlight the potential for implementing EMI-based SHM protocols in various critical applications, thereby augmenting safety and operational efficiency . The research supports the notion that a combination of EMI technology and data analytics can foster a shift towards more proactive maintenance strategies, reducing downtime and maintenance costs, as evidenced by suggestions from recent scholarly articles . Furthermore, the insights emphasize the necessity for further exploration into the environmental factors influencing EMI readings, a consideration echoed in broader discussions surrounding SHM . By advancing an understanding of how impedance dynamics correlate with structural conditions, this research enhances methodological frameworks applicable to real-world engineering challenges, paving the way for future studies to expand on these findings . Consequently, the incorporation of EMI technology within SHM practices not only contributes to theoretical advancements but also presents practical solutions for ensuring the reliability and longevity of composite materials subjected to dynamic loads . Ultimately, this study encapsulates important strides towards forming a comprehensive approach to SHM in complex structures, reinforcing the strategic importance of early detection methodologies in preserving structural integrity and safety . Thus, the findings presented here are vital for guiding future innovations in the development of SHM technologies across various industries. Representative SHM datasets supporting structural monitoring research are summarised in Table 8.

TABLE VIII. STRUCTURAL HEALTH MONITORING (SHM) DATA SOURCES AND APPLICATIONS

Dataset	Description	Source
SDNET2018	Contains 56,000 images of bridge decks, walls, and pavements, suitable for deep learning-based SHM applications.	Maguire et al.
Vibration-based datasets for deep learning	Includes 8,595, 14,465, and 4,800 raw acceleration data samples (9 channels × 10,000 samples each) for bridge state identification.	Zhang et al.
Modal information of 10,300 damage cases	Contains the first seven frequencies and corresponding mode shapes at 14 beam-column joints for damage detection and stiffness reduction analysis.	Pathirage
Wireless vibration-based bolt loosening detection	Comprises 330 signals, each containing 245,760 samples of velocity, for detecting bolt loosening in structures.	Avci et al.
Data anomaly detection and classification	Contains 10,014 time and frequency responses of a long-span cable-stayed bridge, stacked in two channels with a resolution of 100 × 100, for anomaly detection.	Tang et al.

5.3. Future Research Directions

The ongoing advancements in structural health monitoring (SHM) technologies present a fertile ground for future research directions aimed at enhancing the reliability and accuracy of damage detection methodologies. The findings from this study demonstrate that electromechanical impedance (EMI) signals can serve as effective indicators of debonding in sandwich face layers, illuminating pathways for further exploration of various composite materials and configurations . Future inquiries can expand upon the sensitivity analysis established here, incorporating different environmental conditions and material types to assess the robustness of EMI signals in diverse settings, as indicated by literature on similar methodologies . This aligns with previous studies that suggest the need for comprehensive understanding of how different structural parameters and external influences affect EMI readings in real-world applications . Additionally, incorporating machine learning algorithms into the analysis could yield significant insights, guiding automated interpretation of EMI data for faster and more accurate damage assessments . Recent advancements in artificial intelligence lend support to this direction, demonstrating its potential to enhance anomaly detection processes within SHM systems . Furthermore, there lies an opportunity for future research to investigate the seamless integration of EMI technology with other structural sensors, such as fibre optics and acoustic emission sensors, leading to a more holistic monitoring approach that captures multifaceted data on material integrity . Such multi-sensor fusion methods have been shown to offer enhanced diagnostics capabilities, allowing for more nuanced assessments of structural health . Moreover, the concept of implementing self-healing materials within the structure can be explored, integrating EMI monitoring to evaluate the effectiveness of damage repair in real-time . The promise of this avenue is supported by ongoing research into novel materials that can adaptively respond to damage . Ultimately, the implications of these future research directions emphasize the necessity for cross-disciplinary collaboration that bridges materials science, data analytics, and engineering practices, thereby fostering innovative solutions that respond effectively to emerging challenges in structural safety . By addressing these aspects, future studies not only build upon the findings of this research but also contribute significantly to the advancement of SHM methodologies across various industries, promoting safer and more resilient infrastructure . Moving forward, continual enhancements in technology and analytical techniques will be pivotal in shaping the next generation of SHM systems, further ensuring the integrity of critical structures and systems . Key future research directions in electromechanical impedance applications for SHM are summarised in Table 9.

TABLE IX. FUTURE RESEARCH DIRECTIONS IN ELECTROMECHANICAL IMPEDANCE FOR STRUCTURAL HEALTH MONITORING

Research Area	Description	Source
Additive Manufacturing Validation	Developing non-destructive evaluation techniques using piezoelectric materials to detect defects in additively manufactured parts, enhancing the validation process for complex geometries.	NSF Award #1635356
Damage Detection in Concrete Structures	Investigating the sensitivity of PZT impedance sensors for detecting damage in concrete structures, focusing on the structural mechanical impedance as a damage indicator.	Yang, Y., Hu, Y., & Lu, Y. (2008). Sensitivity of PZT Impedance Sensors for Damage Detection of Concrete Structures. Science.gov.
Debonding Detection in Composite Materials	Applying piezoelectric impedance-based health monitoring to identify debonding conditions in composite materials, such as propellant/insulator interfaces in solid rocket motors.	Xiao, L., Chen, G., Chen, X., & Qu, W. (2016). Investigation of Piezoelectric Impedance-Based Health Monitoring of Structure Interface Debonding. NASA Astrophysics Data System.
Sensor Fault Diagnosis	Developing methods for self-diagnosis of piezoelectric sensors using principal component analysis and support vector machines to distinguish between structural damage and sensor faults.	Zhang, Y., & Zhang, L. (2020). Electromechanical Impedance Based Self-Diagnosis of Piezoelectric Smart Structure Using Principal Component Analysis and LibSVM. PubMed Central.
Adhesive Layer Influence in EMI Models	Incorporating the effect of adhesive layers beneath piezoelectric sensors into electromechanical impedance models to improve the accuracy of damage detection in metallic structures.	Zhang, L., & Zhang, Y. (2019). Health Monitoring of Metallic Structures with Electromechanical Impedance and Piezoelectric Sensors. PubMed Central.

6. CONCLUSION

Building on comprehensive investigations into the sensitivity analysis of electromechanical impedance (EMI) signals, the results highlighted EMI signals as a promising tool for the timely detection of debonding in sandwich face layers, an important defect type that manufacturers need to manage in composite materials. The study emphasized the effectiveness of EMI as a non-destructive testing technique, demonstrating that impedance changes are highly correlated with the initiation of structural defects.

Accordingly, this paper proposes an effective solution to the research issue through the presented methodology, which enables more sensitive detection of structural damage, particularly as the bonded area size increases. These implications serve not only academic interests but also provide vital applications in industries that depend on composite materials, including aerospace and civil engineering, where early detection of damage can significantly reduce risk and maintenance efforts.

Furthermore, EMI monitoring technologies have the potential to initiate a paradigm shift in traditional SHM systems by allowing integration into existing structures, eliminating the need to demolish pavements or other elements to conduct structural health assessments. This enables a more proactive approach to structural safety than traditional methods.

Future work may involve investigating more complex composite configurations, as well as complementary approaches using machine learning algorithms for more precise data interpretation and damage prediction. Future studies should also assess the impact of environmental conditions on EMI readings, as external factors can obscure data validity (Mohamad et al., 2022).

Moreover, the potential combination of EMI with conventional sensing technologies could deliver a more comprehensive picture of structural health, complementing already existing monitoring methods. Advancing EMI technologies, as suggested by the findings, calls for more interdisciplinary collaboration to achieve novel materials and systems that leverage EMI more effectively.

The sensitivity analysis validates a promising pathway for refining SHM methods that are already beginning to emerge in the literature, an effort that can be augmented with continued empirical examination. This study, therefore, highlights the role of EMI as one of the key SHM technologies and proposes that broadening its application can significantly enhance the long-term integrity of structures.

The continuation of these research themes will further help to advance the methodology and understanding of SHM practices across various engineering disciplines. Future research can also benefit from the integration of dynamical systems theory, which can further enhance analytical capabilities, enabling more complex studies that can be applied to real structural systems and phenomena.

Overall, this study provides foundational knowledge and tools for future work aimed at improving damage detection approaches and strengthening structural robustness. This shift from theoretical evaluation to practical application will require extensive validation across a range of environmental conditions, as failure modes may vary substantially depending on specific structural applications.

Future research must strike a balance between empirical validation and technological innovation to ensure that developments with EMI technology are both operational and reliable. In conclusion, the sensitivity analysis of EMI signals can lead the way toward better structural health monitoring techniques and represents an exciting first chapter in what is expected to become a longstanding contribution to the field.

6.1. Summary of Key Findings

Investigations into the sensitivity analysis of electromechanical impedance (EMI) signals have yielded considerable findings on utilizing EMI as a low-cost early warning method for the detection of debonding in sandwich face layers, thus highlighting the significance of impedance variation for structural integrity monitoring. This study not only provides a solution for the reliable application of non-destructive testing techniques in engineering applications but also shows that damage deviations within EMI signals can be effectively captured; additionally, drone technology could be explored in future damage assessment efforts in a similar context.

By applying a novel approach that combines advanced signal processing and sensitivity analysis, the study addressed the challenge of late-stage damage detection, offering a preventative strategy for ensuring the integrity of composite materials. These findings could benefit both the academic community, as they add to the existing body of SHM technologies, and practical sectors by contributing to safety and longevity improvements for aerospace and civil engineering infrastructures. Furthermore, the ability of EMI signals to detect early-stage debonding underlines the possibility of optimizing maintenance schedules and minimizing repair costs through timely interventions. One direction for future research is to conduct further studies using a wider variety of composite materials, including increasingly complex geometries and varying environmental conditions that may influence EMI measurements.

The combination of machine learning methods with EMI data processing could significantly enhance predictive capabilities, leading to more reliable damage detection systems. In addition, since environmental factors such as temperature and humidity could significantly impact the accuracy of impedance measurements, further investigations are necessary to fully understand these influences.

Applying this framework to broader structural cases, such as automotive and marine applications, could also prove useful in exploring the scalability of the approach. Moreover, future work could emphasize the development of user-friendly software tools, allowing engineers to quickly interpret EMI data and support real-time decision-making processes.

In conclusion, this study forms a foundational step towards the advancement of structural health monitoring technologies, suggesting that a holistic approach combining EMI with conventional monitoring methods may substantially enhance the overall strength and durability of structures. The results advocate for collaborative efforts in future studies on EMI technologies within SHM systems for engineering applications.

By pursuing these research pathways, the safeguarding of composite materials can be significantly improved, meeting the urgent needs of modern engineering practice concerning safety and quality. Table 10 outlines the progression of damage between different damage states, as well as the accuracy rates of detection derived via EMI sensitivity analysis.

TABLE X. DAMAGE PROGRESSION AND CORRESPONDING DETECTION ACCURACY VIA EMI SENSITIVITY ANALYSIS

Damage State	Damage Progression Index	Detection Accuracy (%)
D0	0.00	N/A (no debond)
D1	0.076	55%
D2	0.26	70%
D3	0.31	85%
D4	0.37	92%

6.2. Implications for Structural Health Monitoring

SHM systems are paramount for developing better composite materials and structures to enhance their safety and lifespan, especially for aeronautical and civil engineering applications where sandwich face layers are used for supporting structures. In this context, the research has carefully investigated the sensitivity of electromechanical impedance (EMI) signals as an early indicator of debonding, proposing that very slight variations in impedance can serve as early warning signs for imminent structural defects.

By applying a well-developed framework for sensitivity analysis of EMI signals, which provides faithful feedback on the material condition, the research has addressed the shortcomings of traditional monitoring methods that fail to detect damage at its incipient stages. This study tackles key issues in non-destructive testing, and the results have substantial academic significance, as well as practical implications that industries can leverage to avoid the risk of undetected structural failures. This work highlights the possibility of implementing such technologies during regular maintenance operations, which can significantly reduce the cost of maintaining infrastructures while increasing their safety assurance, by demonstrating that EMI reliably matches with the early onset of debonding. Therefore, further studies should explore the combination of EMI with complementary monitoring techniques, including optical or acoustic approaches, to deliver a more holistic structural integrity assessment system.

Moreover, investigating the influence of environmental conditions (e.g., humidity and temperature) on the EMI signals, as described in our findings [ ], will broaden the applicability of this technique across diverse operational conditions. Data-driven machine learning algorithms can be employed to enhance analytical capabilities, providing more accurate real-time predictions of damage progression patterns and maintenance needs. Further validation of this methodology for broader applications can be achieved by continuing empirical studies testing EMI's effectiveness under varied conditions.
Additionally, integrating automated data processing systems within SHM setups can ensure quicker decision-making, improving the agility of predictive maintenance strategies (PMS). These findings encourage further exploration into the scalability of EMI technology, emphasizing the necessity of adapting the technology for diverse structural materials and configurations.
In conclusion, the capability of sensitivity analysis to transform EMI signals into reliable early indicators of damage can enable novel practices in SHM, ensuring the reliability and safety of composite structures across various fields. Thus, this work represents a foundational step upon which future advancements can build, aiming ultimately to improve infrastructural resilience and safety.

6.3. Future Research Directions

Based on the sensitivity analysis of EMI signals to detect debonding of sandwich face layers, critical findings in the SHM of composite materials have been reported. To overcome this daunting challenge, this research proposes electromechanical impedance (EMI) techniques as a tool for accurate evaluations of structural integrity much earlier than symptoms appear during damage progression. This is especially relevant when considering the potential application of EMI within maintenance schedules, where it could improve preventative approaches and lessen the chance of premature structural failure.
The study also demonstrates the complex interaction between the variability of impedance spectra and the health of a structure, leading to new paths for SHM techniques that remain relevant to current engineering paradigms. Future research should focus on a more thorough exploration of the types of composite materials evaluated, including novel configurations that may exhibit varying debonding behavior under different service conditions.
Moreover, it is necessary to integrate machine learning algorithms that enhance the predictive capabilities of the knowledge that EMI data can convey, as has been shown to be complementary in other fields exploring pattern recognition and anomaly detection techniques. Understanding the effects of thermal changes and moisture fluctuations on EMI readings is crucial to contextualize how these sensors perform under real-world conditions, which could help validate the robustness of the monitoring system.
Additionally, the application of EMI technology in combination with other Non-Destructive Testing (NDT) methods, such as acoustic emission or optical techniques, could provide more comprehensive insights into the damage evolution mechanisms within composite structures. Real-world case studies should also be conducted to cover a broader spectrum of operational conditions and loading scenarios, which will provide further understanding regarding the performance of EMI for different structural applications.
The application of dynamic systems theory could offer more advanced analytical approaches, resulting in models capable of predicting failure modes through the integration of real-time datasets. Furthermore, partnerships with industry stakeholders can enable the transfer of laboratory findings into real-world applications, allowing EMI technology advancements to directly address the needs of current engineering challenges.
These investigations, in turn, can play a vital role in the advancement of SHM frameworks and enhance the confidence and safety inherent in the use of composite materials across a wide range of industries, including aerospace and civil engineering. Research in this area will continue to develop, but the knowledge gained through these efforts will ultimately allow for improved theoretical models as well as the development of engineering tools that serve to increase the safety and performance of critical infrastructure.

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