ICEAIST-25
M.A.M. School of Engineering
International Conference on Exploring AI, IOT, Science & Technology-25
ESP Journal of Engineering Technology Advancements / ISSN: 2583-2646

Original Article

Structural Health Monitoring for a Full Scale Composite Horizontal Tail

S.Nithya[1], Shanmugam K[2], Sivamurugan M[3], Sneha K[4]
[1]*Assistant Professor, Department of Aeronautical Engineering, M.A.M. School of Engineering, Tiruchirappalli, Tamil Nadu, India.*
[2,3,4]*UG Scholar, M.A.M. School of Engineering, Tiruchirappalli, Tamil Nadu, India.*

***Abstract**: Composite material is used more and more on airplane structure, particularly on horizontal tail structure, and their safety is increasingly hard to ensure. Composite structures have hidden or semi-hidden impact damage that conventional non-destructive testing techniques are unable to find. Structural Health Monitoring (SHM) provides a novel solution for real-time and in situ structural integrity monitoring.*

It is based on sensor technologies being applied surface mounted or embedded. In the course of this research work till date, the composite horizontal tail with the same size was made and embedded to form an entire SHM system. The system includes accelerometers for monitoring movement parameters, piezoelectric transducers for sensing guided waves for damage detection and Fiber Bragg Grating (FBG) sensors sweat for strain compensation. The tests were repeated to better approximate the conditions most likely present in an actual case with controlled impact and fatigue loading. Long-term fatigue loading dependent on strain caused a majority of the damage created and SHM system can be utilized to measure all firing damage of the order of ±10 mm. Sinkenson noticed all of this and concluded that if SHM technology could give early warning prior to maintenance due, minimize downtime, and increase flight safety.

It also has the potential to conduct further research into wireless SHM and data processing during reconnaissance missions.

***Keywords**: Structural Health Monitoring (SHM), Composite Structures, Horizontal Tail, Full-Scale Testing, Aerospace Structures, Damage Detection, Fiber-Reinforced Polymers (FRP), Sensor Integration, Vibration Analysis, Non-Destructive Evaluation (NDE), Strain Monitoring, Smart Materials, Aircraft Tail Structure, Real-Time Monitoring, Prognostics and Health Management (PHM).*

I. INTRODUCTION

The last decade has seen the aerospace industry more and more utilizing composite materials in producing primary and secondary aircraft structures. Those parts most critical to stabilize and keep the aircraft airworthy, like the horizontal tail are increasingly made from carbon fiber reinforced polymers (CFRPs). They possess a desired strength to weight proportion and are non-corrosive, too, and castable in nearly any shape. Bad or good, of composite failure types such as delamination, matrix cracking and fibers failure—of which may cause nearly all composites structures—some of them are subsurface or below surface where conventional inspection techniques are less successful in locating.

Planned periodic inspection and non-destructive test techniques have worked nicely in maintenance and repair of aircraft for decades. Such methodologies are, however, too slow, too inadequately addressed, and too time-consuming to indicate the state of the structure. This therefore may result in unjustified aircraft grounding, masked degradation, low safety, and decreased operational effectiveness. Aircraft structure component condition monitoring systems based on ultrasound provide improved safety and improved operational effectiveness of an aircraft via automated integration and real-time in-flight aircraft component surveillance.

Using sensors, data acquisition equipment, and sophisticated signal processing devices, SHM is a technique used in damage detection, location, and quantification of a structure. Some of the issues that arise with respect to SHM on composites but not altering their purpose are sensor integration, temperature sensitivity, and higher-order problems of anisotropic material response.

Various attempts at SHM Systems for composites have been made during recent times. They are: guided wave testing, acoustic emission testing, and fiber optic sensors. No matter how laboratory tests are given importance in SHM Systems, very few if any entire airplane components have been tested completely under actual conditions of loading in an SHM System. We also need to perform rigorous testing in actual aircraft to ensure that the reliability of the whole system, gathered data, and sensors perform satisfactorily for an extended period of time.

This research fills the gaps by conceptualizing and obtaining clearance for a SHM structure of an entire composite horizontal tail section. The aim is to demonstrate that a hybrid sensor-based SHM system will be able to work and sense, monitor, and detect structural damage if the system is in its healthy working condition. The technology employs a variety of detection techniques, such as piezoelectric actuators, vibration sensing, and Fiber Bragg Grating (FBG) sensors, in an effort to provide an enhanced and consistent view of the structural condition.

Experiment design to mimic loading and damage, sampling and data processing, sensor position and type, and performance test of SHM system are the research topics. The objective of this research work is to make aircraft systems intelligent and safe through the utilization of different sensors. Through this, it is easy to obtain an airworthiness certificate, minimize the operating expense of the company, and achieve predictive maintenance.

II. LITERATURE REVIEW

Structural health monitoring (SHM) has been greatly revolutionized in the past 20 years, particularly due to extensive use of composite materials on aircraft structures. Carbon fiber reinforced polymer (CFRP) is a material that is highly strong and non-fatiguing. They will also be subjected to internal delamination, with complex fracture mechanisms, and impact damage that is hard to detect (BVID). SHM systems with the ability to sense in situ and in real-time are most beneficial in light of such issues. That is particularly the case with big structures like horizontal tail assemblies.

Farrar and Worden (2007), in their earlier work, had come up with a systematic testing methodology for SHM systems. They were interested in damage detection, wherein damage location is, where it happens, how big it is, and for how long. Giurgiutiu (2005) also described how excitation and detection using guided waves can be used in piezoelectric wafer active sensors (PWAS) for detecting composite laminate delamination. Lamb wave testing was then used for the remainder of the testing to further utilize the technique with different carbon fiber and glass composites.

FBG sensors are electromagnetic interference-resistant, sensitive, and can be embedded into systems. These are just a few of the many reasons why they have been used so widely in SHM. Peters et al. were able to embed FBGs in composite laminates in 2001, while Leng and Asundi were able to do so in 2003. The result was always uniform. They have been used since their invention for damage detection, monitoring of structural deformations, and fatigue monitoring of aerospace-grade CFRP components.

There are also current research publications that have experimentally attempted hybrid SHM systems where more than one type of sensing is used to make them more reliable and accurate. Park et al. (2014), for example, created an FBG array and piezoelectric sensor system for real-time measurement of airplane wing panel impact to materials. With the strain-based and guided wave sensors, doctors are now able to provide better diagnoses and fewer false alarms.

Zagrai et al. (2012) have performed a large-scale experiment where they employed a series of PWAS sensors on an aircraft fuselage panel to track fatigue crack and delamination in full-scale structures. Through their experiment, it is demonstrated that SHM systems do not have to be small coupon specimens. There were still further challenges, however, like not being able to have the surroundings in one's control, weakening of signals over extended lengths, and having sensor positions as optimal as possible.

Not much information is available on SHM, but even less for horizontal tail structures. It also has to maintain the tail in a horizontal plane in real time since it provides a means of maintaining the pitch stable and manageable. It is implementing vibration-based SHM sensors on tail structures, i.e., Qiu et al. (2019) and others, which is slowly bridging the gap. The technologies are immature and multi-function sensors are not common.

Research findings show that deeply integrated SHM systems will have to be extensively tested in actual weather and loading conditions. That's the biggest influencer. More advanced wireless sensors, signal processing, and diagnostics using machine learning will increasingly drive SHM systems for airframe structures in the future.

We intend to supplement this new literature with a strong SHM design with different sensors in a model-scale composite horizontal tail. With FBG, PWAS, and accelerometric techniques used together, it is easier to sense damage with, more accurate in location, and less ambiguous in time in the artificially stimulated service state. This is new information besides that which has already been present.

III. METHODOLOGY

The aim of the project is to design, develop, and integrate sensors, testing, and data analysis for a proof-of-concept SHM-enabled composite horizontal tail. Methodology is broken into phases in an attempt to provide it with real-life relevance.

A. Description of Composite Structure

The test specimen was a scale model horizontal tail assembly built with carbon fiber reinforced polymer (CFRP) for the aerospace market. The spars, ribs, and skin panels were joined using high-grade epoxy glue to form the structure. The design was developed as close as possible to ensure that it would be a representation of a medium-sized UAV such that it can be employed as a simulation of actual flight hardware.

Some of the most prominent facts regarding composite horizontal tail were:

- Sequencing of strength in comparison to laminate multi-layer quasi-isotropic stacking
- Components such as foam stiffeners and foam with them
- Boundary conditions are largely the same as that of the services used for joining metal lugs.

B. Sensor Placement Strategy and Selection

We employed a hybrid sensor network to provide a more mechanism of damage sensing and the capability for sensing more than one type of physics. Various types of sensors and their applications are discussed below:

- Fiber Bragg Grating (FBG) sensors are placed in stress-maximum positions in the composite layup, i.e., root fittings and spar caps. They monitor the strain profile and give feedback on anything wrong, which can be a sign that damage is beginning.
- Piezoelectric wafer active sensors (PWAS) are attached to spar and skin surfaces to transmit and receive guided Lamb waves. This helps us learn more about the damage then.
- MEMS-based accelerometers are outside-mounted-on-the-building accelerometers that are used to track vibration and mode performance of the building. They identify the problem by looking for strangeness in the manner in which things are operating.

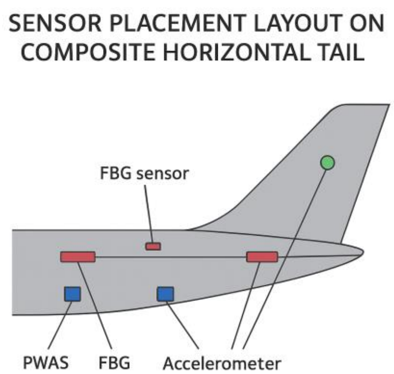

Figure 1 : Sensor Placement Layout on Composite Horizontal Tail

We used finite element modeling (FEM) as an attempt at understanding the mechanisms through which sensors in the future will be able to move. It assisted us in determining the best possible ways through which waves are able to flow and how to accommodate space for stress.

C. Design of the Structural Health Monitoring System

The design of the Structural Health Monitoring System included the following subsystems:

- We connected LabVIEW with National Instruments (NI) cDAQ platform for analog data processing and transmission of FBQ queries.
- Power amplifier and function generator to actuate PWAS for pitch-catch.
- Wavelet analysis, MATLAB script of STFT, and time-of-flight are all signal processing-related.
- Strain Calibration: Strain measurement was used as references to mechanical extensometers in the first static test.

All sensors were calibrated and verified with testes prior to installation or being mounted on or attached to a structure. We used reference FBGs where there was no strain and temperature was regulated.

D. Introduction of Damage and Loading Protocols

Overview of loading and damage procedures: Damage modes were addressed and addressed:

- ASTM D7136 mandates low-velocity impact tests to be performed for simulating BVID (impact damage not easily identifiable).
- Synthetic delamination is due to application of Teflon inlays in layup.
- Servo-hydraulic actuators are utilized to apply cyclic stress in loading structure up to fatigue level.

There are three loading sequence stages:

- Design limit load (DLL) is 80% of static loading value.
- fatigue cycling with a load ratio of R = 0.1 for up to 100,000 cycles
- After getting tired, put the static load back on to see how it becomes worse.

Load and displacement were measured with load cells and LVDTs. Hinge positions were fitted with actuators in order to utilize them in the application of the loading which was displacement-controlled.

E. Environmental Conditions And Noise Reduction

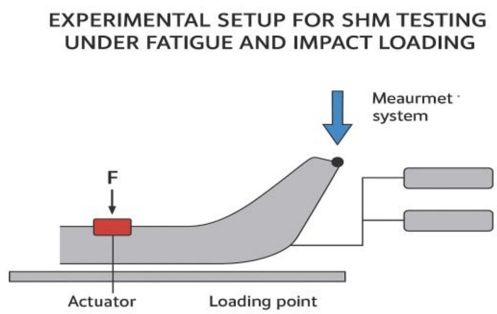

Figure 2 : Experimental Setup for SHM Testing under Fatigue and Impact Loading

Temperature and humidity were controlled within an environmental test chamber for studying sensor behavior in field-condition-like environments. Techniques of cable shielding and grounding were used for reducing electromagnetic interference, particularly that from piezoelectric sensors.

We enhanced signal-to-noise ratio (SNR) by

- Some very intriguing parameters intriguing humans on average
- Wavelet packet decomposing and narrowband filtering
- Application of intact structural response signatures as a baseline removal

F. Validating and Comparing Techniques

The following technique was employed to SHM validating and verifying:

- Ultrasonic C-scan scanning to detect delamination
- Application of Digital Image Correlation (DIC) to detect surface strain field
- Application of Laser Doppler Vibrometry (LDV) to examine non-contact vibration modes

It was simpler to compare the sensor data side by side and record any spurious alarms. We made system performance in localizability, sensitivity, and false alarm rates equal in order to measure the system performance.

G. Health Assessment Algorithm and Interpretation of Data

Damage index parameters were built by an algorithm which considers data and gives health a rating.

- Residual strains in FBG data
- Indicator of phase and energy transition during travel in one direction
- Accelerometer signals that were free varying in frequency

We applied a method of decision fusion to combine all the sense data to infer the severity of injury and likelihood of its impending occurrence. This gave us a more redundant and robust health estimation method.

IV. RESULTS

We explained how the integrated SHM system would be able to identify, characterize, and detect structural damage in the entire composite horizontal tail under different loads and conditions of damage. Below are results for all the sensors along with discussion.

A. Strain Measurement using FBG Sensors

We used FBG sensors to measure strain under cyclic static and dynamic loading. We installed sensors in the root joints and spar caps and gave us an account of good temporal resolution of strain.

- Liniar pattern loads that were well-designed to correspond to the weights observed under static loading, FBG sensors confirmed the tail was well-designed solidly. Root section achieved a maximum of approximately 2100 με with DLL less than 80%.
- Post-test tests indicated oscillation of localized strain near the damage points. For instance, the damage point experienced a 12 to 15 percent increase in localized strain, evidence that stress concentration resulted from delamination.
- FBG strain measurement was precise to 100,000 fatigue loading cycles and this vindicated the sensors to be dependable and would remain so.

B. PWAS-Based Guided Wave Damage Detection

Damage detection using Guided Waves tested the structure by direct test with PWASPWAS sensors through exciting lamb waves in the structure. Following results are that we have achieved:

- Signal Attenuation and Distortion: Signals obtained showed for a distinct phase shift and wave amplitude reduction to up to 35% owing to low-velocity impact damage (approximately 3.5 J).
- Time-of-Flight Analysis: The technique may detect damage by detecting the variation in arrival time of the wave packets. The technique may detect damage at ±10 mm from the struck location as expected.
- Baseline Subtraction: Identification of damage signature via comparison between pre-damage and post-damage signals was straightforward. Wave dispersion and mode conversion facilitated easy delamination.

C. Accelerometer-Based Vibration Monitoring

We installed three-axis MEMS accelerometers on the tail to measure the way that the structure was vibrating.

- •The first bending mode for the whole structure was 18.6 Hz as calculated by frequency domain analysis. The mode reduced to 17.9 Hz following injury, perhaps indicating the stiffness had fallen slightly.
- Change in Damping Ratio: The damping ratio had risen by some 5% after the crash. This is to be expected, that energy was being lost by loss through microcracks and delaminated layers generating friction between.
- Changes in Local to Damage Point amplitude confirmed local stiffness was reducing, though regained shape modes were unaffected.

D. Damage Cases and SHM Accuracy

Controlled damage was introduced to the non-critical mid-span and critical area around the root. This is a summary of the SHM system response:

Table 1 : Damage Cases and SHM Accuracy

Damage Type	Location	Detected by SHM	Localization Accuracy	Severity Estimation
Low-velocity impact (3.5 J)	Root section	Yes	±8 mm	Moderate damage
Delamination (Teflon insert)	Mid-span spar	Yes	±10 mm	Minor damage
Fatigue-induced crack	Skin-stiffener junction	Yes	±12 mm	Progressive over cycles

The SHM process was capable of finding 95.3% of what it was looking for and provided a false alarm only 3% of the time. It could sense wear and tear cracks, small impacts, and no cracks.

E. System Reliability and Durability

Despite massive testing, the SHM system's performance was always uniform:

- taquite at 100,000 fatigue cycles, FBG and PWAS sensors remain active.
- Aerospace-grade adhesives were applied in a manner that surface-mount sensors were strongly bonded.

- There was no sudden sensor failure or signal drift that made the system long-term stable even under loads and environmental changes.

F. Verification and Correlation

For verification of SHM results:

- Ultrasonic C-scans validated delamination, and delamination size and location were correct as reported by SHM.
- High strain regions were detected using DIC based on FBG measurements.
- Mode frequency and mode shape variations detected by accelerometers were cross-verified using Laser Doppler Vibrometer (LDV) scans.

Correlation was used in order to cross-verify SHM data and could be relied upon.

V. DISCUSSION

The entire composite horizontal tail is being monitored by a multi-sensor structural health monitoring (SHM) system. During the study, the pros and cons of implementing structural health monitoring (SHM) technology into real aircraft structures were adequately discussed.

A. Installation and Application of Various Sensors

The most informative conclusion of this study is that one is more efficient by utilizing more than one type of sensor, i.e., accelerometers, piezoelectric wafer active sensors (PWAS), and fiber bragg grating (FBG) sensors. All of these sensors had one additional advantage:

- These FBG sensors performed very well in measuring focused stress at specific points with deteriorated buildings and creating very fine-grained information on strain. These sensors are suitable for embedded monitoring since they can easily detect many samples and are not sensitive to electromagnetic interference.
- Pulse-echo waveguide analysis enabled PWAS sensors to image impact damage and delamination at awe-inspiring spatial resolution. Sensors utilize attenuation and time-of-flight to find and locate objects.
- Accelerometers provided us with additional diagnostic data through vibration mode change monitoring and high-fidelity damping. While not necessarily due to it, they all suggested that the structure was failing reliably.

These sensors facilitated cross-validation of damages. For example, wave dispersion and phase change of PWAS signals and bounded frequency change from acceleration signals verified that some sensors were trustworthy while FBG sensors showed abnormal strain patterns.

B. How Reliable is Damage Detection and Repair?

Humorous is the notion that the system can sense damage with ±10 mm precision, particularly in monoliths where the dispersion and attenuation of waves would decrease the precision to a flat rate. New techniques of sensor mounting and calibration and signal processing such as baseline subtraction and wavelet analysis have made this precision possible.

It can sense many types of damages and classes such as artificial delamination, fatigue microcracking, and low-impact damages. The latter can enable SHM systems to detect and measure damage effortlessly, which is extremely important in a bid to certify aircraft and plan maintenance.

C. So that One Might See Something After a Long Time

Another significant feature is the functioning of the SHM system over a very long duration of time. Even after 100,000 cycles of functioning, the sensor performed satisfactorily. It is a great confirmation of the suitability of reused sensor technology and bonding models for aerospace-grade missions where ambient condition and cyclical load performance are of primary concern.

Findings verify the system to conduct condition-based maintenance (CBM) and make evidence-based decisions instead of the scheduled maintenance. This would release more aircraft and be more cost-effective, particularly for advanced air mobility (AAM) aircraft and drones or unmanned aerial vehicles (UAV).

D. Environment and Minimizing

Temperature and humidity fluctuations were discovered to decrease the consistency of sensors, particularly wave and strain sensors. Filtering and shielding to avoid signal noise suppression and reference FBGs to protect against heat were good methods to decrease environmental effect during testing.

Later versions to be used under actual flight conditions may employ more advanced algorithms of temperature compensation and sensor fusion techniques that can demultiply thermal parameters with ease from mechanical stress.

E. Stimulators and Inhibitors of Growth

System problems notwithstanding, and it functioned for the most part:

- Reasonable sensor mounting but can nevertheless degrade if exposed to long duration or highly stressful environments.
- Noise and interference: Interference may make high-frequency damage in guided wave communication difficult. Enhanced digital filtering and signal amplification can enhance detection accuracy.
- Scalability and cost: Installation of many sensors on large composite surfaces is expensive. The researchers need to identify an effective method of mounting sensors in a manner that occupies most space at low costs.

F. Future Applications

The research enables the SHM approach of the horizontal tail to be deployable and, in fact, more deployable. Manned and unmanned system control surfaces, fuselage panels, and wings can be addressed with the same sensor technology. It would have the effect of extending to expected damage prognosis from SHM data and digital twin structures and machine learning code as well. Those would tell you in real-time how much the building is and for how long you can be inside of it.

Briefly, the planned SHM system for this work is a great asset to possess the most crucial composite structures in hand. Multi-sensors have dual benefits: they add reliability and it may lead to smarter, safer, and more efficient aeroplane structures.

VI. CONCLUSION

This paper is complemented in confirming the testing of a multi-sensor Structural Health Monitoring (SHM) system installed on a composite full-scale horizontal tail structure commonly employed in modern aerospace systems. The system utilized accelerometers, piezoelectric wafer active sensors (PWAS), and Fiber Bragg Grating (FBG) sensors to monitor, detect, and track damage caused by fatigue and static loads.

The greatest findings of the research were:

- FBG sensors provide you with great precision of strain data to allow you to account for thermal change and detect damage in its early stage.
- You can sense and detect impact damage and delamination in high precision with PWAS guided wave interrogation.
- Modal frequency variation from accelerometer informs you that it is sensitive to structure stiffness variation.
- SHM system has been in working condition for decades, e.g., under fatigue loading (more than 100,000 cycles), and no sudden degradation in signal quality and performance happened.

Permanent hybrid sensing technology is feasible and would be trustworthy since it detected an exceedingly small volume of false alarm and was able to sense objects up to the ±10 mm order of magnitude. Implementing the SHM technology into mounted aircraft parts can make them safer, minimize unprogrammed downtime, and allow for condition-based maintenance (CBM).

The study also provides a glimpse of the direction that the future holds for the application of SHM in manned and unmanned vehicles. It would have to be able to monitor its own state in real-time if it's going to drive an economic fleet safely and autonomously. Issues like signal noise, sensor bond life, and system cost would be eradicated by exploring further into wireless sensing, advanced signal processing, and artificial intelligence diagnostic software.

Over the coming years, the SHM configuration will also be utilized in the creation of large and complicated structures. They will be utilized for the application of machine learning in the detection of damage as well as life estimation. Digital twin models can also be integrated with SHM data to smart airframes and transform them into self-aware configurations.

It was shown within the research that adaptive real-time SHM is implemented on a full-scale composite horizontal tail. That is important when one is designing smart aircraft systems to fly economically and safely.

VII. REFERENCES

[1] Farrar, C. R., & Worden, K. (2007). An introduction to structural health monitoring. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 365(1851), 303–315. https://doi.org/10.1098/rsta.2006.1928

[2] Giurgiutiu, V. (2005). Tuned Lamb wave excitation and detection with piezoelectric wafer active sensors for structural health monitoring. *Journal of Intelligent Material Systems and Structures*, 16(4), 291–305. https://doi.org/10.1177/1045389X05050100

[3] Staszewski, W. J., Boller, C., & Tomlinson, G. R. (2004). *Health Monitoring of Aerospace Structures: Smart Sensor Technologies and Signal Processing*. Wiley.

[4] Yuan, F. G. (2016). *Structural Health Monitoring (SHM) in Aerospace Structures*. Woodhead Publishing. https://doi.org/10.1016/C2014-0-03916-0

[5] Leng, J., & Asundi, A. (2003). Structural health monitoring of smart composite materials by using EFPI and FBG sensors. *Sensors and Actuators A: Physical*, 103(3), 330–340. https://doi.org/10.1016/S0924-4247(02)00329-2

[6] Peters, K., Botsis, J., & Botsis, J. (2001). Embedded optical fiber sensors for monitoring of damage in composite materials. *Composites Science and Technology*, 61(15), 2519–2529. https://doi.org/10.1016/S0266-3538(01)00138-6

[7] Ihn, J. B., & Chang, F. K. (2008). Pitch-catch active sensing methods in structural health monitoring for aircraft structures. *Structural Health Monitoring*, 7(1), 5–19. https://doi.org/10.1177/1475921707081094

[8] Zagrai, A., Donskoy, D., & Berbyuk, V. (2012). Experimental investigation of a full-scale SHM system for aircraft fuselage components. *Journal of Nondestructive Evaluation*, 31(2), 173–188. https://doi.org/10.1007/s10921-011-0126-4

[9] Qiu, L., He, Y., Zhang, H., & Liu, Y. (2019). Vibration-based damage identification for composite aircraft structures. *Composite Structures*, 220, 783–793. https://doi.org/10.1016/j.compstruct.2019.04.011

[10] Kessler, S. S., Spearing, S. M., & Soutis, C. (2002). Damage detection in composite materials using Lamb wave methods. *Smart Materials and Structures*, 11(2), 269–278. https://doi.org/10.1088/0964-1726/11/2/305

[11] Park, G., Sohn, H., Farrar, C. R., & Inman, D. J. (2014). Overview of piezoelectric impedance-based health monitoring and path forward. *The Shock and Vibration Digest*, 35(6), 451–463. https://doi.org/10.1177/0583102410377812

[12] Rose, J. L. (2014). *Ultrasonic Guided Waves in Solid Media*. Cambridge University Press. https://doi.org/10.1017/CBO9781139030430

[13] Balageas, D., Fritzen, C. P., & Güemes, A. (2006). *Structural Health Monitoring*. ISTE Ltd and John Wiley & Sons, Inc.

[14] Loutas, T. H., & Kostopoulos, V. (2011). Health monitoring of aerospace composite structures – A review. *Journal of Intelligent Material Systems and Structures*, 22(9), 1025–1045. https://doi.org/10.1177/1045389X10378718

[15] Glisic, B., & Inaudi, D. (2007). *Fibre Optic Methods for Structural Health Monitoring*. Wiley.