

A Feasibility Study of Debonding Detection in Multi-Layered Marine Thin-Wall Structures Using a Non-Destructive Vibration-Based Approach

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ABSTRACT

This study analyses different debonding defect scenarios on a multi-layered material composed of carbon fibre-reinforced polymer as a composite coating applied to structural steel, with the aim of applying it to marine structures. The study utilises vibration-based experimental non-destructive diagnostics and numerical simulations to thoroughly examine the debonding extent at four different lengths: 0%, 25%, 75%, and 100% of the total length of the material. The theoretical formulation of the free vibration of the proposed material for the fully bonded condition (0%) is also established using classical beam theory and the principles of composite materials. The four initial natural frequencies in the analysis provide indirect observations of the strength and stiffness properties. The results demonstrate that a reduction in the natural frequencies with increasing debonding size is mainly attributed to a loss of stiffness, rather than to the mass and stress distributions between the layers. Although debonding significantly affects the structure at longer lengths, only a small effect is observed when debonding covers 25% of the length. Based on the results, the experimental methods demonstrate strong agreement with the numerical approaches for determining natural frequencies, despite the unexpected results for the fundamental frequency of vibrations in the theoretical approaches. Eventually, we show that the prediction model established for this purpose accurately predicts the impact of debonding defects on the vibration characteristics of a structure with a high coefficient of determination.

Keywords: marine structures, debonding, non-destructive diagnostics, vibration-based testing, innovation systems

INTRODUCTION

In the marine industry, the need for multi-layered structures which are highly resilient to environmental impacts and exhibit excellent structural integrity has increased significantly. This aspect remains especially vital in the case of offshore stationary structures which, unlike typical ships, cannot easily be delivered to a shipyard for thorough inspection and overhauling. Structures composed of multiple layers are widely adopted in aerospace, automotive, and civil engineering, due to their outstanding properties. However, it has limited practical uses in the maritime sector (e.g. for

constructing entire ship hulls) due to several considerable challenges.

Recent studies [1,2] have shown that harmful environmental conditions, including wave-induced loads, saltwater exposure, and high humidity, significantly degrade the structural performance of these materials over time. In addition, [3] demonstrated that a conventional structure with a painted surface deteriorates over time, inevitably leading to a reduction in performance and necessitating costly repairs in the absence of timely maintenance [4]. Traditional techniques for retrofitting older structures involve removing and replacing plates or, rarely, attaching steel plates

to the damaged area using bolts or welding. Nevertheless, this technique also presents several drawbacks to the overall system [5].

In response to these challenges, multi-layered, thin-walled structures, comprising fibre-reinforced polymers (FRP) layered onto steel, have emerged as a potential solution for retrofitting and upgrading traditional steel structures. Within the realm of FRPs, carbon fibre reinforcement (CFRP) has been proven to be suitable for meeting the increased demand of some marine structures, owing to its exceptional strength, high stiffness, low weight, and resistance to corrosion [6-8] numerical, and experimental means. The effectiveness of externally bonded reinforcement (EBR). However, CFRP layered with metallic structures introduces new challenges, particularly related to hidden damage, fibre breakages, and cracks [9] especially in aerospace structures. To optimize the design of the delaminated composite panels under compression loading, accurate characterization of the effects of different parameters such as features of the initial defect, the curvature of the laminate, and layup stacking sequence on the post-buckling behavior play a significant role. In this research, after a comprehensive review on the main previous researches, by implementing a Cohesive Zone Model (CZM, [10]), as well as problems related to load transfer between layers of dissimilar materials. The interfaces between these layers are vulnerable to differences in material properties, such as stiffness, making them susceptible to failure under fluctuating environmental conditions, such as temperature and wave-induced loads. The repetitive stresses caused by these conditions cause smaller cracks to propagate at the bonded interface, eventually leading to debonding or layer separation. In contrast to common failure modes, like hidden damage and delamination, debonding exhibits a distinct feature due to the improper load transfer between layers resulting from wave-induced loads.

Therefore, debonding between the layers, caused by factors such as wave-induced loads, is a critical issue that compromises structural integrity and performance. Since debonding is a precursor to the occurrence of corrosion, understanding its behaviour provides a foundation for addressing marine-specific challenges, including the long-term impact of corrosion. Debonding directly influences the vibration properties of a material, including its natural frequencies and vibration modes. The issue with this specific defect is that it appears in a variety of shapes and sizes in the real marine environment (e.g. patch-like, circular, or irregular patterns), depending on operational and environmental conditions.

Failing to detect or address these damages in their early stages can lead to catastrophic failures, potentially causing significant economic losses. This situation underscores the critical need for early-stage techniques to identify and assess the severity of this damage in layered composite materials.

Several non-destructive techniques for detecting and identifying structural damage have gained popularity, including ultrasonic testing, infrared thermography, shearography, terahertz testing, acoustic emissions, X-rays,

neutron imaging, and digital image correlation [11]. Although each of these non-destructive testing approaches has potential, it is rare to obtain complete structural integrity, as they are often localised and only capable of inspecting a specific area [12]. The necessity for quantitative global damage identification, without previous knowledge of the damage location, has driven the development of approaches that assess changes in structural vibrations, known as vibration-based damage detection [13]. Extensive research has been conducted on vibration-based modal analyses, to examine the mechanical strength and damage mechanisms in composite materials and structures [14]. The vibration energy method has been examined as a novel vibration-based damage detection and critical performance indicator for identifying and measuring delamination in composite bulkheads. [15] analysed the dynamic behaviour of curved shell panels simultaneously subjected to both cracks and delamination under thermo-mechanical loading, using both numerical and experimental approaches. [16] introduced a new index, known as the Improved Curvature Damage Factor (ICDF) for identifying and localising defects in carbon fibre composite laminates. [17] developed a novel technique that used mode shapes to correctly identify and localise delamination in composites under different damage conditions, which comprises damage locations at the centre, corner, and both the centre and the corner. In [18], the delamination of Glass Fibre reinforced (GFR) composite beams was evaluated using an ANN algorithm with the natural frequencies of vibration as a potential parameter. Shifts in the natural frequency is the most widely used vibration parameter for determining structural failures because it is highly sensitive to changes in structural rigidity [19]. Nevertheless, the majority of researchers did not consider changes in natural frequency as being enough of a deterministic method for identifying defects in composites materials with multiple layers [20]. Although several vibration-based non-destructive testing techniques have been widely adopted, detecting debonding within multi-layered marine structures remains a largely unexplored area in the context of marine applications. A notable gap exists in the field, as there is a lack of effective diagnostic techniques for identifying debonding in CFRP-steel composites subjected to marine specific challenges.

Therefore, for the sake of filling this revealed knowledge gap, this study examines different debonding scenarios for recently developed CFRP-steel layers, focusing on shifts in natural frequencies as a possible vibration-based diagnostic method. The study mainly emphasises the innovative aspects of material selection, debonding pattern, and diagnostic techniques.

The advancement in this study represents a significant contribution to the field, particularly in the context of layered materials, where frequency-based diagnostic techniques have been under-utilised. The relevance of this work lies in its novel approach for investigating the impact of debonding on the vibration characteristics of multi-layered marine structures. It further demonstrates the potential of the established diagnostic techniques for detecting such defects.

By addressing the critical need for multi-layered structures and effective diagnostic tools, the proposed materials and technologies will alleviate the high demands placed on marine structures. This output from the study has the potential to minimise maintenance costs, extend service life, and prevent catastrophic failures, thereby improving overall structural performance and corrosion prevention. The remainder of this paper is organised as follows: Section 2 describes the materials used in the study and elaborates on the applied methodology; Section 3 presents the obtained results along with related discussion; and Section 4 concludes the paper.

MATERIALS AND METHODS

MATERIALS USED FOR THE INVESTIGATION

The materials used in this investigation were CFRP layered on structural steel with established mechanical properties, as listed in Table 1. One of the advantages of using CFRP as a composite coating is its unique corrosion resistance, high strength, and high stiffness, which makes it suitable for marine applications. All experimental investigations were performed on a two-layered material, as shown in Fig. 1. It can be considered as a rectangular beam with dimensions of 500 x 100 mm and varying thicknesses and debonding sizes. Accordingly, samples were initially prepared with debonding sizes of 0, 25, 75, and 100% of the total length of the sample material. The preparation process began with precise cutting of the materials to meet the established requirements and maintain homogeneity between the samples. The surfaces of both the steel and composite materials were carefully cleaned to remove contaminants using a cleaning solution. This technique was used to improve the adhesion quality and prevent interference during bonding. Subsequently, an epoxy-based adhesive was applied to the material surfaces. This adhesive was selected because of its excellent bonding properties, corrosion resistance, and longevity in maritime settings. To guarantee optimum curing qualities, the epoxy was mixed according to the manufacturer's specified weight ratio. This method ensured electrical insulation and protection against galvanic coupling, which is critical for avoiding corrosion at the steel-composite interface.

Tab. 1. Material properties [6]

Materials	CFRP	Steel
L*W [mm]	500*100	500*100
Density [kg/m ³]	1598	7850
Elastic Modulus [GPa]	90.1	209.0
Poisson ratio	0.32	0.28
Thickness [mm]	1	4

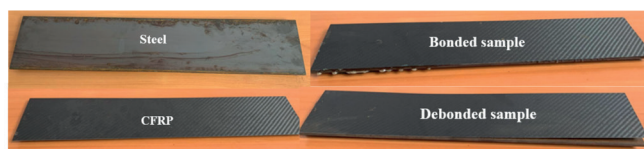


Fig.1. Sample materials used in the investigation

EXPERIMENTAL PROCEDURES AND METHOD OF ANALYSIS

For the experimental analysis of debonding defects in multi-layered thin-wall structures, various standard measurement devices, and their specifications, were established at the Faculty of Mechanical Engineering and Ship Technology, as shown in Fig. 2. Vibration tests were conducted using an impact hammer (PCB Piezotronics 086D05) connected to an acquisition system (Quantum MX840B) with multiple channels for recording data. A hammer was used to excite the structure, which was chosen for several reasons, including its ability to excite multiple modes and broad frequency ranges, as well as its sensitivity to high-frequency modes that would be difficult to capture using other excitation techniques. These capabilities made it suitable for complex structures. The hammer was used to strike the structure in its middle and the spikes in the time-domain signal were then frequently examined for inconsistencies. This process was repeated until we obtained a clear time-domain signal capable of accurately distinguishing the frequency components that describe the structural characteristics. However, it has been observed that while performing free vibration analysis to evaluate natural frequencies, the excitation force and position have no significant effect on the results. This is because the natural frequencies are inherent characteristics of the structure, defined by its mass and stiffness. Therefore, hammer strike serves as a way of imparting energy to the system and initiating the vibration. The structure then vibrates at its natural frequencies, regardless of the force magnitude or striking location.

The accelerometer sensors shown in Fig. 2 were used to measure the response of the structure to external excitations, with two single-axis accelerometers (ASC P101A15 - T51) placed on the sample surface to capture acceleration data in the vertical *y*-direction. Employing this transducer offers significant advantages, in terms of measurement accuracy, without the need for specialised sample preparation. This simplification reduces the need for specialised sample preparation, placing the sensor inside the debonding region.

The initial phase of the experimental procedure involved the measurement of the vibration characteristics of the bonded sample, followed by the measurement of the dynamic characteristics of the debonded sample under several debonding conditions. Since vibration-based methods are sensitive to environmental factors, it is essential to take steps to avoid inaccuracies caused by these conditions. To guarantee the reliability of the experiment, signals across all

samples were collected and analysed using appropriate signal processing techniques, followed by repeated measurements. The natural frequencies measured by the two attached accelerometers were averaged across all samples. This allowed us to obtain relevant information from the samples, rather than relying on individual measurements, which may be more susceptible to environmental impacts. To strengthen the accuracy of the experimental results and control over the environmental impacts, parallel simulations, which provided a more controlled and idealised representation of the system, were also conducted.

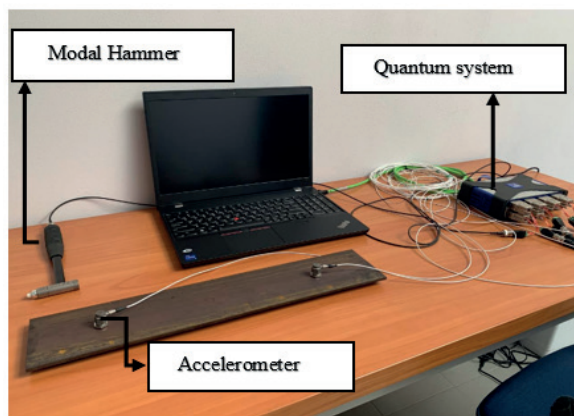


Fig. 2. Experimental setup of the measurement system

The signals collected from the experimental measurements were initially represented in a time domain in which the response was at a sampling frequency of 38 kHz for two seconds. After the time-domain signal was obtained, the Fast Fourier Transform (FFT) algorithm was used to decompose the signal into its frequency constituent, which makes up the signal in the time domain. FFT is a highly optimised algorithm that efficiently converts discrete signals from the time to frequency domain. Therefore, the frequencies of a signal and the individual contributions of each frequency can be identified during the analysis, to determine certain properties that are correlated with the natural frequency of vibrations as indirect observations of the strength and stiffness characteristics.

Finite element numerical simulations

As previously discussed, the complex nature of multi-layered structures and the failures associated with their composition may not be properly described under real experimental conditions because of the different material characteristics of the layers. In such cases, a numerical method would be more suitable for simulating such a complicated process, with a few reasonable assumptions. Finite element techniques are considered accurate and flexible numerical approaches for modelling and solving such problems.

The present study used ABAQUS software to create and analyse a 3D finite element model for different debonding

conditions in multi-layered structures. The process of model definition begins with the creation of the geometry specifying where the precise layouts of the steel and CFRP layers, as well as the interface where debonding could occur. The material properties and geometrical parameters considered in the experimental studies were also employed in the numerical simulations, as depicted in Fig. 3(a), which illustrates the geometries, coordinate systems, and assembly of the numerical model. The mesh size, type, and shape are also crucial in numerical analysis because they facilitate accurate simulation of the process. The element type and size are primarily determined by the model size, complexity, and the type of analysis. In this study, a continuum three-dimensional eight-node reduced integral (C3D8R) linear brick element with hexahedral shape was used, as shown in Fig. 3(b).

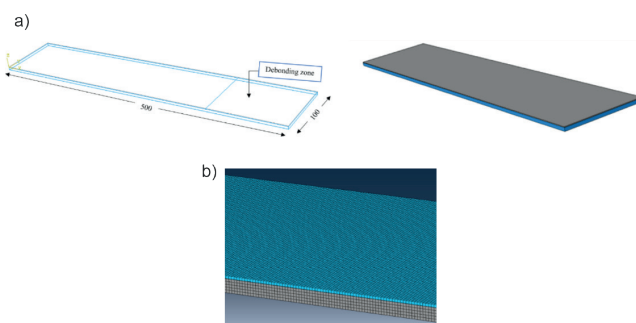


Fig. 3. (a) Material geometry with dimensions (b) mesh model of material

Theoretical equations

A vibration-based analysis of the debonding defects was performed by quantifying the changes in the measured structural response. The response can be characterised by the modal parameters of its natural frequency, which are potential indicators of structural stiffness. However, the composition of the steel and CFRP layers makes it difficult to determine the stiffness of composite materials. Therefore, the classical beam theory given by Eq. (1) and the principles of composite materials were utilised for the theoretical calculations of the angular frequency in the first specimen (0%) debonding. For harmonic vibrations, the solution to the governing partial differential equation yields an ordinary differential equation, Eq. (2). The angular frequency, which is used to determine the natural frequency of vibration, is given by Eq. (3). These two approaches consider the composite structure to be a composite beam, where the effective stiffness of the beam is considered as the cumulative stiffness of each layer and given by Eq. (4). The formulation considers a few assumptions to simplify and address non-uniform material properties by creating an equivalent beam that involves the estimation of the effective stiffness.

$$EI \frac{\partial^4 y}{\partial x^4} + m \frac{\partial^2 y}{\partial t^2} = 0 \quad (1)$$

In the context of the free vibration of a beam, E is the modulus of elasticity, I denotes the second moment of the area, and y denotes the transverse deflection.

$$\frac{d^4 \phi}{dx^4} + \lambda^4 \frac{d^2 y}{dt^2} = 0, \quad \lambda^4 = m\omega^2/EI \quad (2)$$

$$\omega_n = \lambda n^2 \sqrt{EI}/m \quad (3)$$

$\lambda n = n\pi/l$, where λn is n^{th} root of the natural frequency associated with its mode number and mainly depends on the boundary conditions of the beam.

$$Ee = \sum EI_{steel} + EI_{cfrp} \quad (4)$$

RESULTS AND DISCUSSION

This section presents the results of evaluating different debonding situations in multi-layered structures. Although the first four initial frequencies were displayed on the signal, the analysis revealed higher frequency values, suggesting that the excitation methods under investigation are effective and can handle a broad range of frequencies instead of only lower

natural frequencies. Despite the capability and high sensitivity of the system at higher frequencies, there is a lower chance of resonance in this frequency range.

MODAL PROPERTIES OF A FULLY BONDED CFRP-STEEL STRUCTURE (0% DEBONDING)

The experimental analysis of a perfectly bonded condition was primarily aimed at a baseline for examining the natural frequencies of the structure and to gain an understanding of the material response for different debonding sizes. Fig. 4(a) shows the signals from a fully bonded CFRP layered with steel structures, in which the two layers are perfectly bonded together. The signals clearly show that the two installed accelerometers almost registered the same magnitudes of frequencies, regardless of their positions and impact location. The results demonstrate that accurate debonding detection can be accomplished using only two single-axis accelerometers, reducing the need for specialised sample preparation in the measurement system, to accommodate sensors inside the debonding region. However, a notable difference in the very high resonance in the second natural frequency of vibrations occurred because of the intense localised energy resulting from the relative positions of the accelerometers and impact sites. This requires the thorough investigation of the proper placement of sensors, to enhance the detection and characterisation of the responses. The average of the two

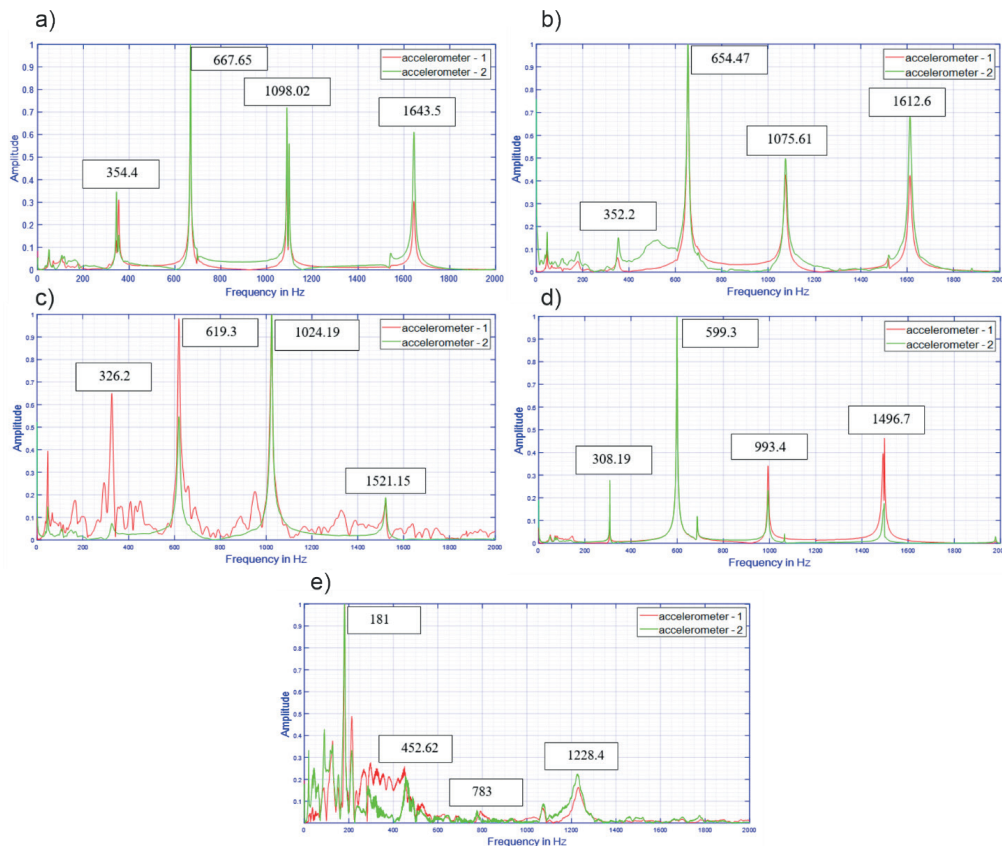


Fig. 4. Natural Frequencies across Various Debonding Levels: (a) 0%, (b) 25%, (c) 75%, and (d) 100% Debonding, along with (e) CFRP

accelerometer responses was used to guarantee the precision of the measurements. The signal also demonstrates that the location of the sensors, relative to the defect, can affect the intensity of the vibration, which is distinct from its magnitude. Furthermore, the signal presents a few minor additional peaks with negligible effects on the vibration properties, which can be attributed to the slight movement of structures during the measurement process. The peaks observed at frequencies below the fundamental frequency are frequently related to measurement errors. The first four numerically simulated vibrations, which describe the behaviour of the structure in real experimental investigations under the given debonding conditions, are shown in Fig. 5.

Comparisons between the numerically simulated frequency values, including the theoretical approaches, are presented in Table 2. The remaining conditions examined in the experiment were compared to perfectly bonded scenarios, which served as a baseline for determining the impact of debonding defects on the vibration characteristics.

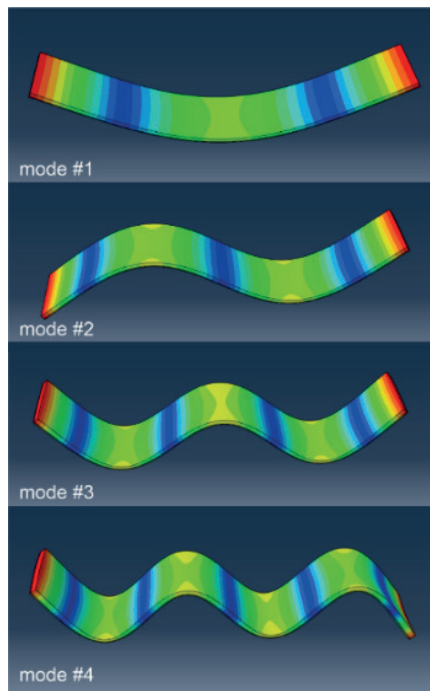


Fig. 5. Numerical simulations: mode shapes of fully bonded CFRP-Steel structure

Tab. 2. Measured and calculated natural frequencies of the experimental, numerical, and theoretical approaches for (0%) debonding

Mode	Experimental (Hz)	Numerical (Hz)	Error	Experimental (Hz)	Theoretical (Hz)	Error
1	354.10	380.72	7.5%	354.10	204.90	42.1%
2	667.67	665.70	0.2%	667.67	564.80	15.4%
3	1098.02	1032.00	6.0%	1098.02	1107.30	0.8%
4	1643.50	1789.30	8.8%	1643.50	1830.57	11.3%

Tab. 3. Measured and calculated natural frequencies of the experimental and numerical approaches for (25%) debonding

Mode	Experimental (Hz)	Numerical (Hz)	Percentage error
1	352.2	328.8	6.6%
2	654.4	653.7	0.1%
3	1075.6	1009.2	6.1%
4	1612.6	1760.4	9.1%

Tab. 4 Measured and calculated natural frequencies of the experimental and numerical approaches for (75%) debonding

Mode	Experimental (Hz)	Numerical (Hz)	Percentage error
1	326.2	322.5	1.1%
2	619.3	650.3	5.0%
3	1024.1	947.5	7.4%
4	1521.1	1554.7	2.2%

Table 5: The measured and calculated natural frequency for the experimental and numerical approaches for (100%) debonding

Mode	Experimental (Hz)	Numerical (Hz)	Percentage error
1	308.19	280.5	9.0%
2	599.30	637.5	6.3%
3	993.40	921.9	7.1%
4	1496.70	1508.9	0.8%

CHARACTERISTIC INFLUENCE OF 25% DEBONDING

The vibration characteristics of the 25% debonded sample are shown in Fig. 4(b). The frequency at which the maximum resonance peak occurs shifted to 352.2 Hz for the first natural frequency, 654.47 Hz for the second, 1075.6 Hz for the third, and 1612.6 Hz for the fourth, when compared with the resonance frequency under fully bonded conditions. These shifts clearly suggest a change in the natural frequency of the system, which is likely to be related to the presence of debonding defects along the shortest length. However, upon thorough examination of this condition, it is clear that debonding at this magnitude has a relatively negligible impact on the overall structural integrity, compared with a fully bonded CFRP-steel structure. As a result, when debonding magnitudes are small, the structure maintains a greater stiffness value because the undamaged bonded area keeps distributing and withstanding external forces, such as wave-induced and other dynamic loads. Therefore, debonding at this magnitude has not yet severely influenced the material's ability to resist deformation, which implies that strength and stiffness remain relatively unchanged.

The smallest peaks identified on the left-hand side of the fundamental frequencies were most likely caused by measurement errors in the fully bonded specimen. These smallest peaks had no substantial effect on the vibration characteristics of the structure because the magnitudes associated with these frequencies produced negligible vibration patterns and had no impact on the overall structural strength. Thus, their presence is more indicative of experimental artefacts than actual structural defects. Generally, although debonding alters the natural frequencies of the system, the structural response remains relatively stable in the 25% debonding case, which provides an insight into the sufficient

stiffness that allows the structure to function effectively under normal conditions. However, it is crucial to monitor and address debonding defects of any magnitude because they may progress and potentially compromise the structural integrity. The simulation results, which closely correlate the 25% debonding conditions with the experimental results, are presented in Table 3. The results accurately replicate shifts in the natural frequencies observed in the experimental analysis. This correlation confirms the reliability of the experimental results related to debonding defects and validates the accuracy of the predictions made under these conditions.

CHARACTERISTIC INFLUENCE IN 75% DEBONDING

The influence of debonding on the vibration and stiffness characteristics of a structure was more significant under the 75% debonding condition than under the first two debonding extents. From Fig. 4(c), although the drop in the first three natural frequencies is not considerable, compared with that of the bonded sample, these frequencies demonstrate resonance, indicating that the structural vibration is highly amplified. This means that even relatively small external forces can result in a large vibrational response, potentially causing structural damage due to the elevated stress and strain within the material. However, the magnitude of the fourth natural frequency undergoes a significant change compared with the resonance conditions, indicating that resonance occurs more frequently within a lower range of frequencies than at higher values. In addition to the resonance phenomena, the results demonstrate that debonding generates additional peaks and anti-resonance frequencies, along with the deterioration of smoothness in the vibration spectrum. These irregularities in the frequency response indicate a loss of structural stiffness and integrity due to the introduction of additional vibrational modes resulting from debonding. Furthermore, the high vibration response can be attributed to the complex interactions between the bonded and debonded regions of the layer. These interactions can lead to the formation of a localised stress distribution and decrease the overall stiffness, making the composite more vulnerable to dynamic forces. The results also indicate that the natural frequency values associated with steel were inherently higher than those associated with CFRP. Conversely, Fig. 4(a) illustrates that the CFRP layered on the steel structure also improves the stiffness characteristics and the natural frequency of vibrations for perfectly bonded conditions, compared with steel alone. Therefore, the noticeable drop in the natural frequency at 75% debonding, compared to 0% debonding, is most likely attributable to the magnitude of debonding and, in some cases, the bonding quality rather than any inherent problems of the CFRP and steel properties. The findings from the 75% debonding simulation, as listed in Table 4, revealed a strong correlation with the experimental data in anticipation of the natural frequencies of vibrations under extreme debonding magnitudes.

CHARACTERISTICS OF COMPLETELY DEBONDED STEEL STRUCTURE (100% DEBONDING)

The experimental analysis of the fully debonded conditions presented in Fig. 4(d) provides valuable insights into the behaviour of a steel structure that lacks carbon fibre-reinforced polymer (CFRP). The signals demonstrate that the smoothness and consistency profiles of the curves remain largely unaffected, suggesting that steel possesses excellent stiffness properties and resistance to deformation. This inherent stiffness enables a steel structure to retain its integrity under certain external excitations. The natural frequency values for these debonding conditions, determined both experimentally and numerically, are listed in Table 5. The deviations between the two approaches were slightly greater than those in the other scenarios. In all of these cases, deviations may arise due to several factors. The most important factor could be the numerical models, which often involve simplifying assumptions such as an idealised geometry and neglecting external factors (e.g. environmental conditions and manufacturing defects), which may not adequately represent the actual experimental conditions. Material characteristics may also contribute to these differences. In practice, differences in material properties can lead to discrepancies between the two approaches.

In contrast, the fully bonded multi-layered structure exhibited substantial variation compared to steel without a reinforced polymer. The reinforcement provides a notable increase in stiffness, suggesting that CFRP is not only used for coating technology but also significantly upgrades the stiffness characteristics and load-carrying capacity of steel when they are layered together. The results in Fig. 5 show the first four mode shapes of the CFRP-steel structure. The mode shapes obtained for the separate steel and CFRP were the same; however, their associated natural frequencies were different. The natural frequencies associated with the stiffness properties are more significant for the multi-layered CFRP-steel structures. Fig. 6 shows the percentage contribution of the CFRP to the vibration characteristics. The results show that CFRP contributes 14.9% to the first natural frequency, 11.4% to the second, 10.5% to the third, and 9.8% to the fourth compared with steel, which lacks this reinforcement. Since CFRP has a significantly lower density than steel, its contribution to the overall inertial mass of the structure is negligible. This reduced effect on mass ensures that the vibration characteristics, particularly the natural frequencies, remain large.

According to Fig. 6, retrofitting CFRP on steel structures provides minimal additional weight to the structure and resists deformation under a variety of stresses, including those experienced in maritime conditions such as wave loads. As a result, in addition to corrosion resistance, the use of CFRP layered on steel provides significant structural performance improvements. However, the severely deteriorated signals in Fig. 4(e) for CFRP frequently revealed inconsistencies in the structural response, owing to its low stiffness properties for external excitations because the same magnitude of

excitation frequency in the steel structure was used to excite this material.

Rigorous verification of the experimental results is indispensable to ensure the accuracy and reliability of the methods undertaken, which consistently produce excellent outcomes. The frequency components derived from experimental, numerical, and theoretical approaches, along with the percentage errors under perfectly bonded and debonded conditions, were calculated and are presented in the previous section. The interactions between these frequency values are compared in Fig. 7, which displays significant trends in the structure, such that the natural vibrations increase as the debonding decreases throughout its length.

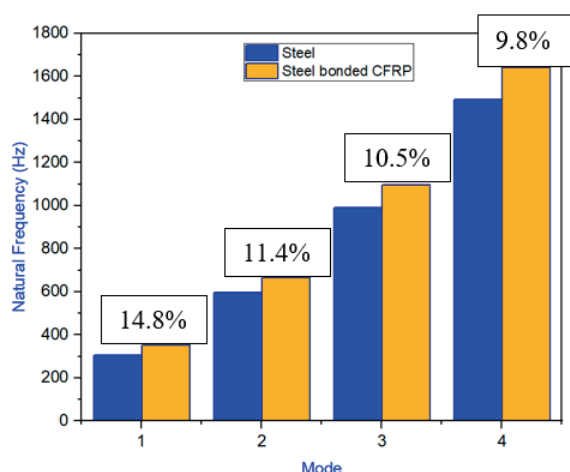


Fig. 6. Percentage improvements in the natural frequencies of steel structures with CFRP

Furthermore, the results from the graph confirm the validity of the experimental approaches compared with the numerical results, despite the unexpected result for the fundamental frequency of vibrations in the theoretical approaches, which deviated more significantly from the experimental results. Several factors contributed to the discrepancies in the results.

First, a considerable number of model simplifications result in inaccurate descriptions of the actual structural behaviour. In addition, the approach involves oversimplified assumptions or mathematical formulations that fail to account for complex structural dynamics. This means that the theory only considers one-dimensional bending along the length of the structure. However, in real scenarios, the vibration modes occur in two dimensions, which the theoretical model fails to consider. Furthermore, uncertain material properties and environmental factors may contribute to the differences between measured and calculated natural frequencies. The impact of all these characteristics is more pronounced in the fundamental mode of vibration due to its global nature and lower frequency. As a result, accurately characterising the material characteristics, particularly the anisotropic nature of multi-layered materials, may result in improved accuracy in the theoretical model. Furthermore, applying more realistic boundary conditions in theoretical models, which are similar

to the experimental setups, might contribute to minimising discrepancies.

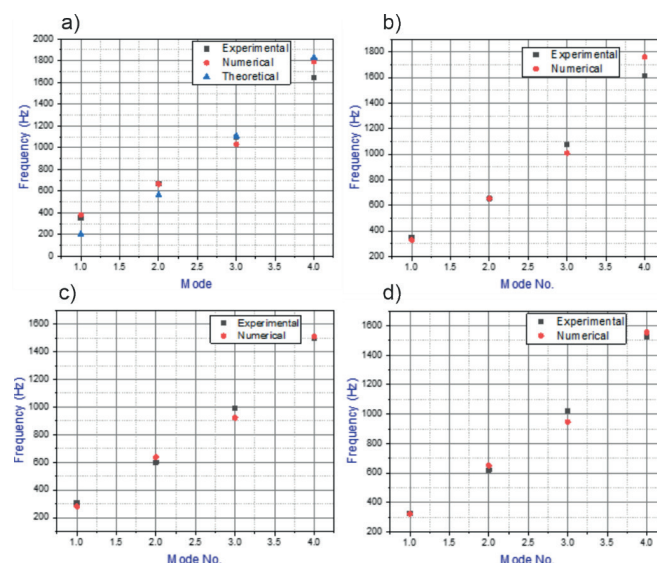


Fig. 7. Comparison of the first four natural frequencies for (a) 0% , (b) 25% (c) 75% (d)100% debonding

Despite the limitations of scarce experimental datasets, the efficiency of the measured results can also be verified using predictive analysis, which estimates the influence of debonding defects on the natural frequencies of vibration. The fitted equation for a general linear model that predicts the relationship between the two parameters is shown in Fig. 8. The accuracy of this correlation can be evaluated using the coefficient of determination R^2 , as shown in Fig. 8. The coefficient of determination is a statistical measure that provides information on how closely the data should be fitted to a regression line. From the figure, remarkable R^2 values were obtained for all natural frequencies of vibrations, indicating the accuracy and reliability of these models in predicting the changes in the natural frequency associated with the specified debonding conditions. These findings show that the proposed models successfully capture the impact of debonding on vibration characteristics, providing a strong framework for analysing and predicting structural behaviour.

It is important to acknowledge the limitations of this study and their potential influence on the thoroughness of the results and broader implications. Although this study offers significant insights into the impact of debonding on multi-layered structures, the sample size employed in the investigation was relatively limited, potentially affecting the generalisability of the findings. Future research should include a larger number of experimental samples and numerical modelling to validate the outcomes across various techniques. Debonding in maritime environments can take various shapes and sizes, such as patch-like, circular, or irregular patterns, depending on operational conditions. The aim of this study was to address structures of various shapes and sizes, along with unknown damage conditions in a real marine environment. Future investigations are

necessary to examine a variety of materials, such as GFRP, and different parametric factors that affect structural health, such as improper sensor placement, defect locations, and different geometrical and material properties. Moreover, it is very important to study the influence of marine-specific parameters, such as temperature, salt-water exposure and

humidity on the debonding and vibration characteristics. These factors should be considered in future studies, to provide a more comprehensive understanding and develop a novel predictive model that can optimise the performance of multi-layered structures.

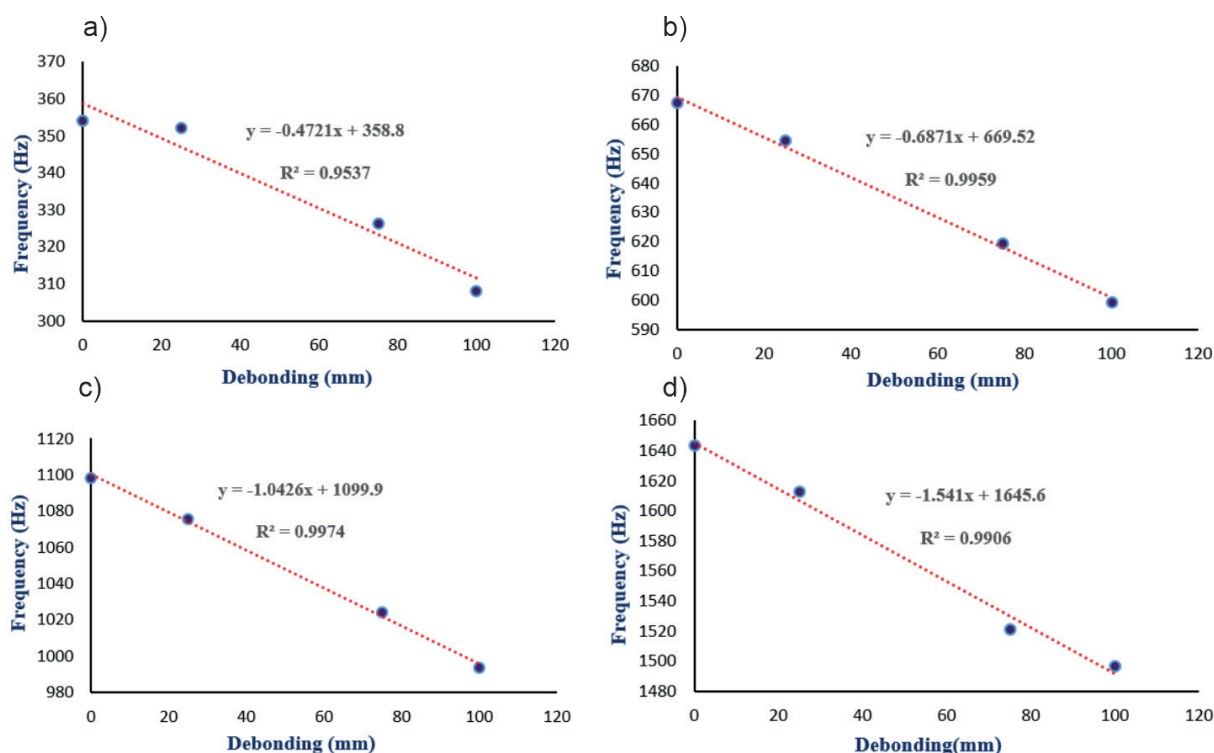


Fig. 7. Regression analysis of the debonding effect on the (a) first (b) second (c) third (d) fourth natural frequencies

CONCLUSIONS

This study investigated the influence of debonding on the vibration characteristics and stiffness of multi-layered structures. Using non-destructive vibration-based techniques, the impact of debonding on the proposed material was accurately identified and the research objectives were successfully achieved. The results of the analysis show that reductions in the natural frequencies with increasing debonding size can be attributed to the loss of stiffness due to the elevated stress within the material. Despite the significant impact of debonding along larger lengths, a small variation in the natural frequency, which was 25% of the length, was observed at the beginning of debonding. Through a comprehensive analysis, this study demonstrates vibration-based shifts in natural frequency, and provides a more global and comprehensive diagnostic tool for detecting debonding in multi-layered structures with a simple accelerometer configuration. In addition, the predictive model established for this purpose accurately predicted the impact of debonding defects on the natural frequency of vibrations with a high

coefficient of determination, indicating the efficiency of the proposed non-destructive method of analysis. Moreover, this study highlights the effectiveness of CFRP in enhancing the strength and vibration properties of traditional steels. The output of this study has the potential to alleviate the high demands placed on marine structures by extending their service life and preventing catastrophic failures, while improving structural strength and corrosion prevention. Future investigations are necessary, to examine a variety of materials and different parametric factors, such as marine-specific parameters that affect structural health, with the goal of developing a novel predictive model that can optimise the performance of multi-layered structures.

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