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Research Article

Elliptical Method for Damage Identification in Carbon Fibre Reinforced Polymer Laminates

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Oftentimes, researchers in the area of vibration-based structural health monitoring (SHM) and damage detection focused their attention on the global properties of structures, which are modal frequencies and modal damping factors. However, the effect on the local properties for SHM, that is, modal constants, has not been extremely explored. In this paper, the elliptical plane modal identification method is proposed to be used as a damage identification method itself. It is observed that when the receptance is plotted in the elliptical plane, the area of the ellipse formed close to the resonant frequencies (which depends on the modal constants) can be used to detect damage, namely, composite carbon fibre reinforced polymer (CFRP) rectangular plates. Although a mathematical correlation has not been established yet, results show that the method is sensitive to the presence of damage in the test plates, as the area of the ellipse changes with damage.

1. Introduction

The ever-developing world as continuously demanded an advancement in every field of endeavour to meet up with the increasing desire for a better society yet does not have a damaging effect on the environment. In the field of engineering, a composite carbon fibre reinforced polymer (CFRP) is one of such materials that has shaped and challenged several industries such as marine, aerospace, civil infrastructural, and automotive and sports equipment, owing to their rare mechanical properties, namely, strength and stiffness to weight ratios [1–5]. Despite the unique mechanical properties of CFRP, low-impact damages have been its shortcomings. Such damages may be introduced, for instance, by a hailstone, bird strike, debris, stones, or tools drop during manufacturing/maintenance [6]. Medium-to-low energy impacts (i.e., 1–10 m/s and 11–30 m/s, respectively) on the surface may result in BVID (barely visible impact damage), i.e., in a mark other than a small indentation that is difficult to identify through visual inspection. However, the impact may have resulted in damage that propagates under different mechanisms through the thickness of the laminate down to the opposite side which is usually hidden. This could compromise the integrity of the structure, reduce the remaining useful life (RUL) [7], and raise safety issues. Hence, it is pertinent to implement systems that can promptly identify and locate damage in composites in order to avert an unexpected breakdown of structures.

Several nondestructive techniques (NDTs), such as acoustic emission, ultrasound, visual inspection, X-ray, or eddy currents, among others [8], have been developed over the years in an attempt to get a more efficient, simple, and economical solution for monitoring and detection of damage in composite structures. However, no single technique has proven appropriate for all circumstances. Each technique has its uniqueness, effectiveness, and range of applications. It would be beneficial to develop a method that could detect damage in a structure based on its global properties through vibration testing. In that regard, researchers have engaged in continuous studies in the area of the analysis of the vibration characteristics of structures to identify damage without prior knowledge of the location of the damage.

The method is hinged upon knowing the state of the healthy characteristics of the structure and using it as a baseline to compare with the vibration characteristics of the structure at a planned period or at its damaged state. The comparison would highlight any noticeable deviation in the case of the presence of damage and might even reveal the damage location and its severity.

An extensive review on SHM and techniques for damage detection has been presented in [9–11]. Montalvão et al. [12] presented a review of vibration-based SHM with special emphasis on composite materials. Among other damage identification methods, modal analysis is the mostly applied technique [13]. This method utilises the deviation in the modal parameters (modal frequencies, modal damping, and mode shape) of a structure. The dynamic behaviour of the structure is analysed based on the modal parameters extracted from the raw data collected. The modal properties can be used to monitor vibration and damages in a CFRP.

It is difficult to analyse the interactions between all the features of mechanical systems. However, the dynamic properties of the mechanical system can be represented if the basic properties are assumed to be a single-degree-of-freedom (SDOF) system and considered separately [14]. The dynamic characteristics of structures can be described with spatial, modal, or frequency response model as stated by Maia and Silva [14]. It is interesting to note that these models can be linked with each other [14, 15]. The spatial distribution of mass, stiffness, and damping properties are illustrated in terms of matrixes of mass $[M]$, stiffness $[K]$, and damping $[D]$ (for the hysterically damped model) or $[C]$ (for the viscously damped model) [14, 15].

Over the years, researchers have always been focusing on the global properties of structures for SHM, with little interest in the local properties—the modal constants. This work explores the plausibility of damage identification with the modal constants. This study focuses on understanding the possible relationships between the deviation in the ellipse area and damage. The modal constants of the CFRP material determine the area and shape of the ellipse.

2. Materials and Methods

2.1. Materials Preparation. In this investigation, laminates with dimensions as shown in Table 1 were manufactured and used to conduct the experimental modal analysis. The composite consists of plain weave carbon fibres as the reinforcement and epoxy as the matrix.

It is a unidirectional (UD) prepreg FIBREDUX 6268-HTA (12K) carbon/epoxy material. HexPly® 6268 provides good adhesion to honeycomb core and suitable for aircraft structures. All the test samples were manufactured using the hand layup, and a bagging film (Nylon 66) that can withstand high temperatures and pressures was used during the curing process. The bagging process can be seen in Figure 1.

To avoid sticking of the prepreg laminates to the aluminium plate (forming tool), the prepreg laminates were sandwiched between two release films. The vacuum bag was sealed with an inner yellow sealant tape; the pressure gauge and vacuum pipes were connected to the vacuum bagging through valves. For the autoclave curing cycle, start-up heat was 20°C and heat up rate was 1°C/min until it reached 121°C. The laminates were cured at 106 kPa for 2 hours and then naturally cooled.

2.2. Vibration Testing. The composite plates were suspended vertically under a free-free simulated configuration with 2 nylon strings as shown in Figure 2. A force transducer is attached at the corner of the specimen and connected to an electromagnetic shaker through a pushrod (stinger).

The response of the samples due to the generation of a multisine [16] excitation signal for a frequency range of 0 to 800 Hz with a frequency resolution of 0.25 Hz was measured. The responses were measured at a specific location using three lightweight PCB teardrop accelerometers, type 352A24, that weighs 0.8 g each, at the corner of the specimen to acquire the Frequency Response Functions (FRFs). The experiments were performed for both healthy and damage-induced samples of the same configuration.

A number of experiments were conducted by assembling/disassembling, and results were generally consistent although a statistical analysis was not formally conducted.

2.3. Static Testing. In order to introduce damage in the specimen, static testing (ST) was performed using a 25 kN Tinius-Olsen universal testing machine. This technique has been followed by other authors in the absence of impact testing machines, such as [3, 17]. The experimental setup for the ST is illustrated in Figure 3.

An indenter made from carbon steel with a hemispheric tip of 24.5 mm in diameter was used. The setup consists of a 350 mm^2 rectangular fixture base plate with a cutout of 250×150 mm. A total of six vertical toggle clamps hold the specimen to the fixture base, three spaced equally on each side of the length of the fixture base. The specimen is clamped to the base plate to avoid movement during loading. The ST was conducted at a loading speed of 10 mm/min, with the application of varying force. After each round of loading, the energy dissipated on the test plates was within the range of 0.41 kJ to 18 kJ. The study considered five different stacking sequences, and they are labelled in alphanumeric style, that is, plates A1, A2, B1, B2, C1, C2, D1, and D2, as shown from Figures 4–6.

Since the area and the shape of the ellipse depend on the real and imaginary modal constants, a possible deviation in the area of the ellipse due to damage would suggest a correlation. The area of the ellipse from the test specimens was identified using the elliptical method [18–20]. The ellipse

Table 1: Types of specimens and designations.

Quantity	Designation	Material	Stacking sequence	Laminate type	Dimensions (mm)	Aspect ratio (a/b)
2	Plate A1–A3	FibreDUX 6268C-HTA 12K	$[90/\pm45/0]_s$	Quasi-isotropic	$310 \times 240 \times 2$	1.29
2	Plate B1-B2	FibreDUX 6268C-HTA 12K	$[90/0/\pm45]_s$	Quasi-isotropic	$310 \times 240 \times 2$	1.29
2	Plate C1–C3	FibreDUX 6268C-HTA 12K	$[90/0]_{2s}$	Cross-ply	$310 \times 240 \times 2$	1.29
2	Plate D1	FibreDUX 6268C-HTA 12K	$[90_2/0_3]_s$	Cross-ply	$310 \times 240 \times 2$	1.29
1	Plate E1	FibreDUX 6268C-HTA 12K	$[90_3/0_3]_s$	Cross-ply	$300 \times 241 \times 3$	1.24

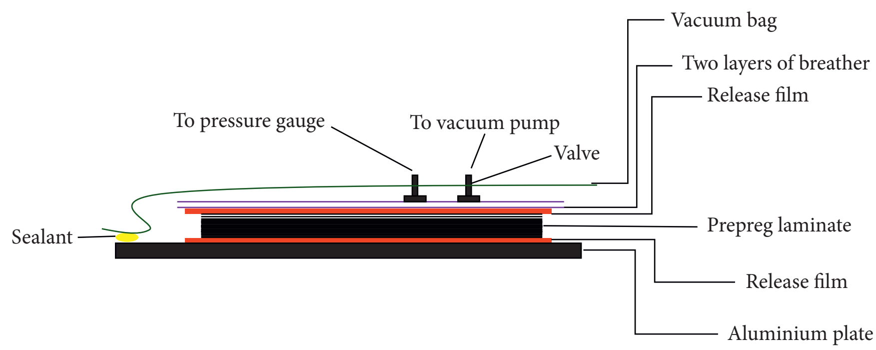


Figure 1: Vacuum bagging process.

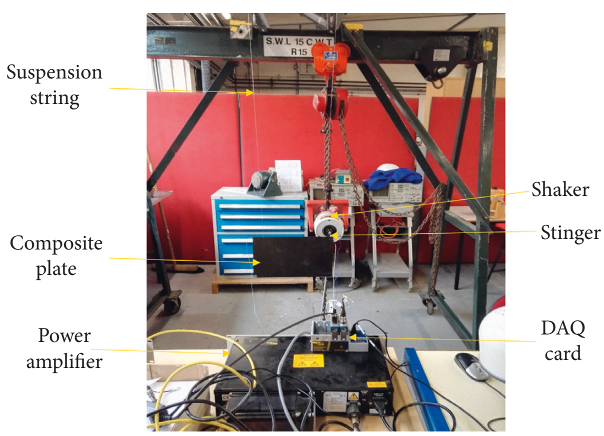


Figure 2: Experimental setup for vibration testing [6].

modal identification software can also be used to determine the global properties of a structure, that is, the modal frequency and modal damping.

3. Results and Discussion

The theoretical development of the elliptical method and its properties are presented in [18]. The elliptical method depends on the modal constants—the real and imaginary parts of the modal constant. The real part of the modal constant can be determined by using the following equation:

$$A_R = \sqrt{H^2_{\omega=\omega_r}\eta_r^2\omega_r^4 - A_I^2}, \tag{1}$$

while the imaginary part of the modal constant is determined by using the following equation:

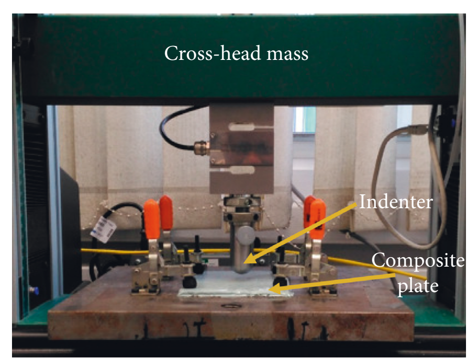


Figure 3: Static testing.

$$A_I = \sqrt{\frac{H^2_{\omega=\omega_r}\eta_r^2\omega_r^4}{\left[\tan\left[\sin^{-1}\left(\theta_{\omega\ll\gg\omega_r}\right)\right]\right]^{-2} + 1}}, \tag{2}$$

where A_R is the real part of the modal constant, A_I is the imaginary part of the constant, H is the amplitude of the receptance, ω is the natural frequency, ω_r is the angular frequency for mode r, η_r is the hysterical damping factor for mode r, and θ is the phase angle between the force and the displacement response. From the results, it was observed that the presence of damage in the CFRP reduces the area of the ellipse. Some representative elliptical shapes are shown in Figures 7 and 8.

The amplitudes of the healthy and damaged ellipse for plate A1 shown in Figure 7 are multiplied by 5 and 10,000 scale multipliers, respectively. Despite a large amount of multiplier, the area of the ellipse for the damaged plate is relatively smaller than that for the healthy plate. This

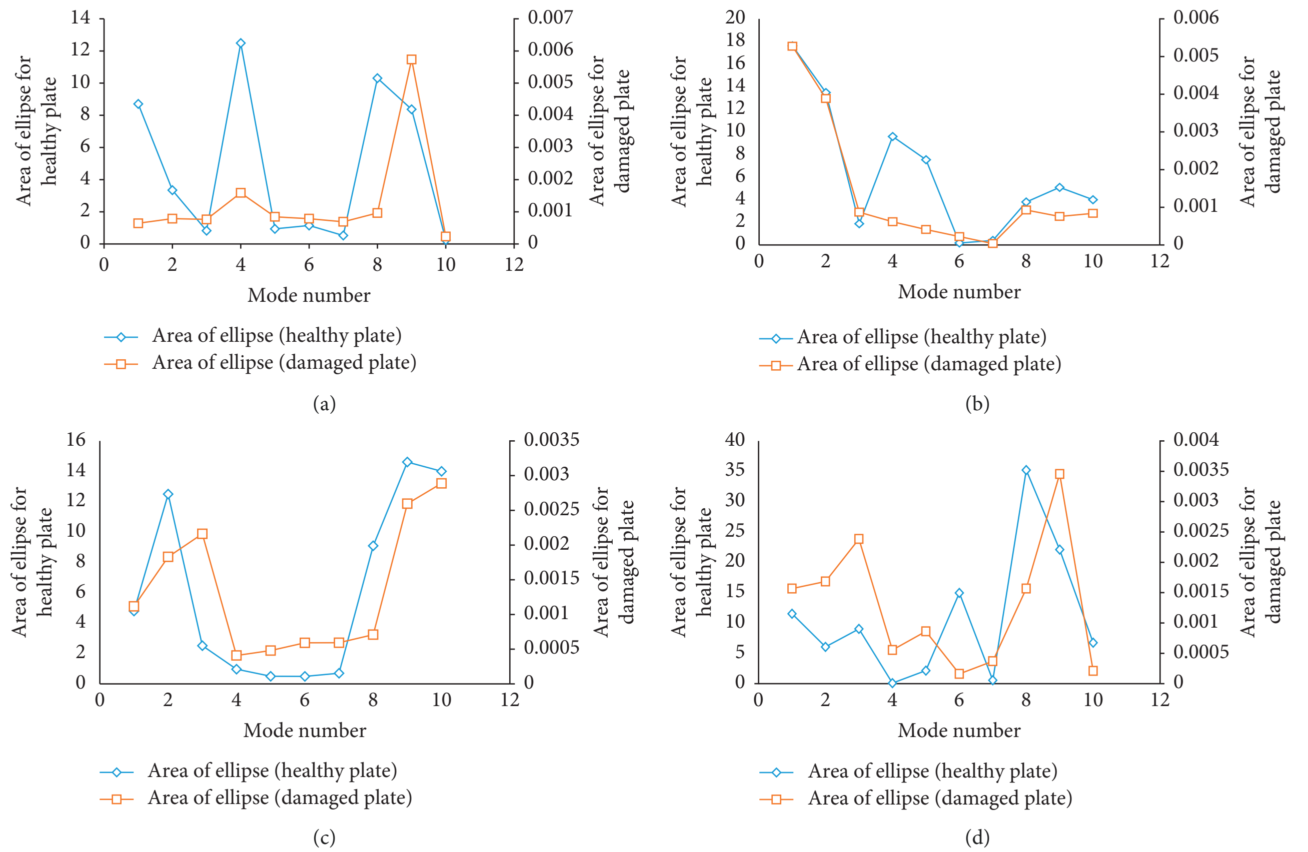


Figure 4: Variation in the area of the ellipse for plates (a) A1, (b) A2, (c) A3, and (d) B1.

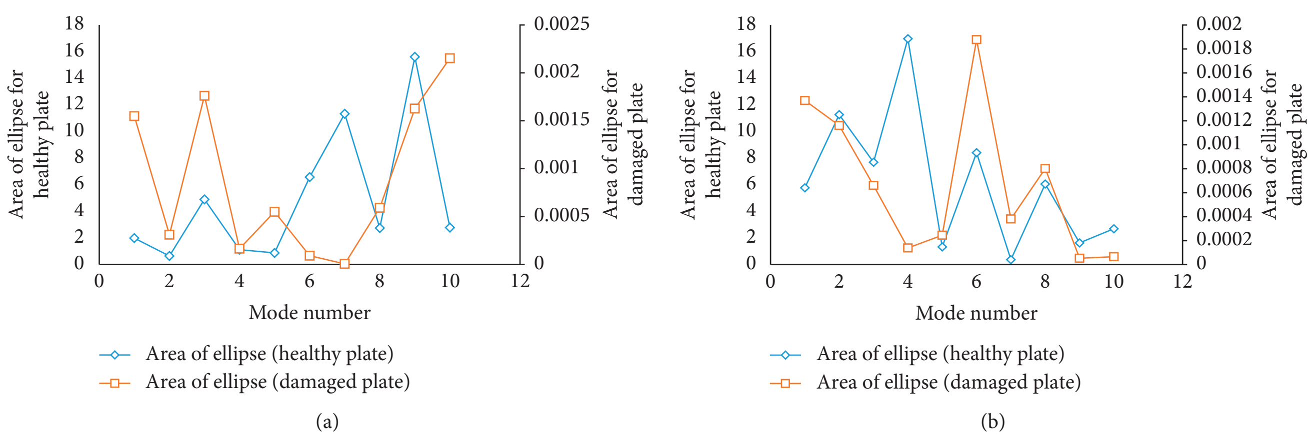
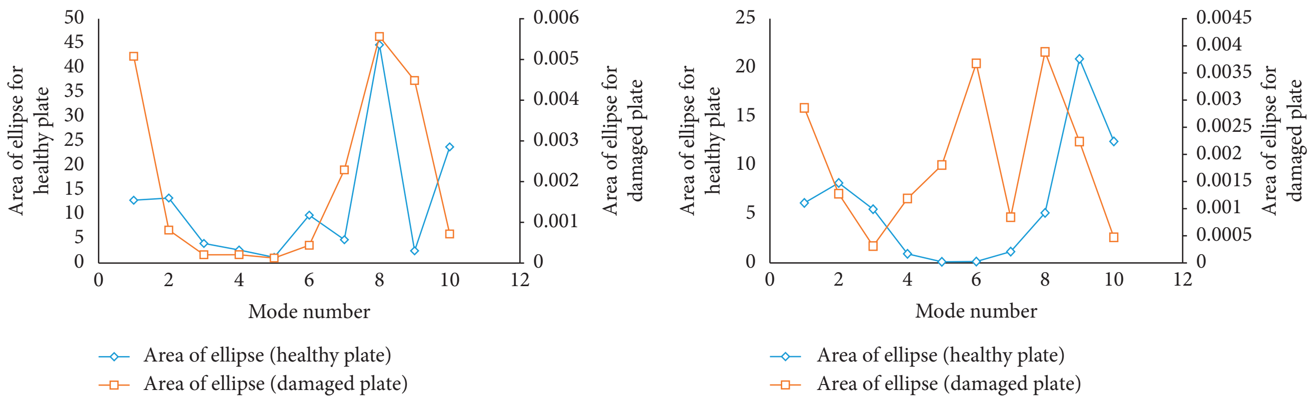
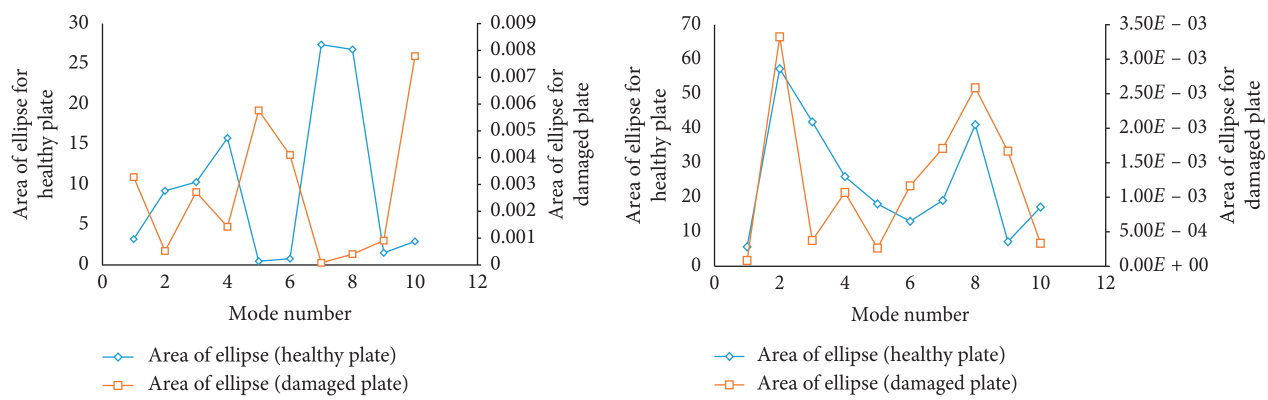


Figure 5: Continued.



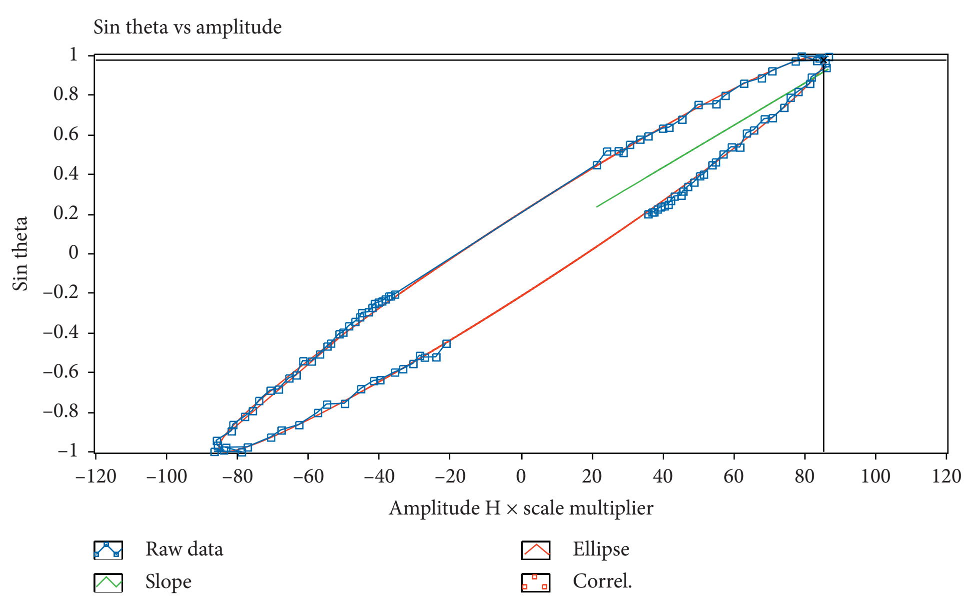
(c) (d)

FIGURE 5: Variation in the area of the ellipse for plates (a) B2, (b) C1, (c) C2, and (d) C3.



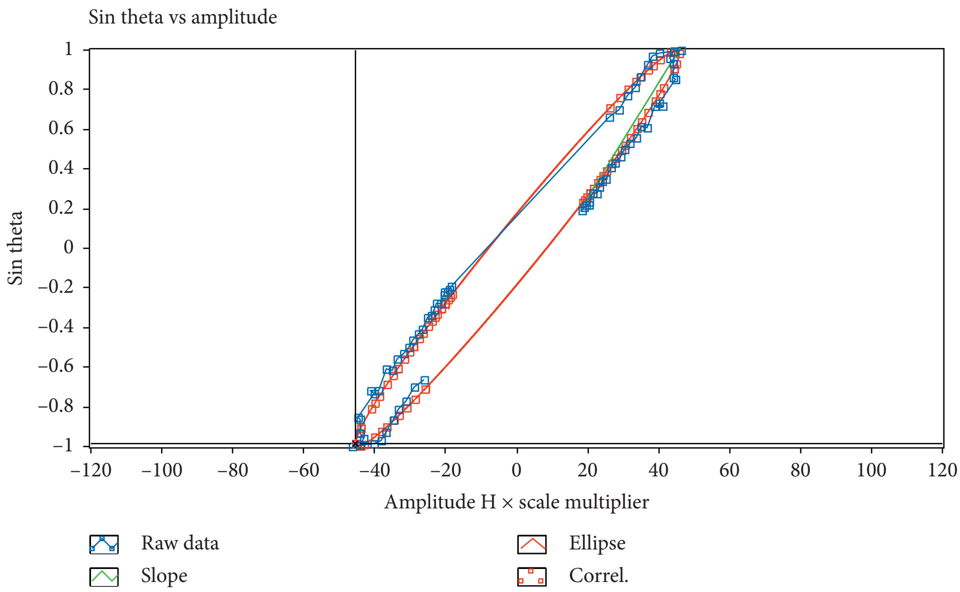
(a) (b)

FIGURE 6: Variation in the area of the ellipse for plates (a) D1 and (b) E1.



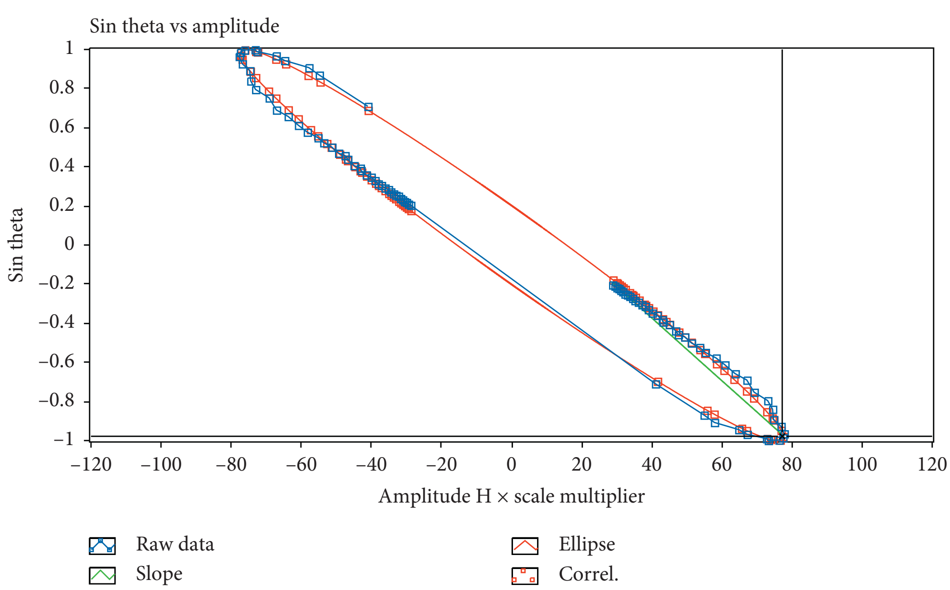
(a)

FIGURE 7: Continued.



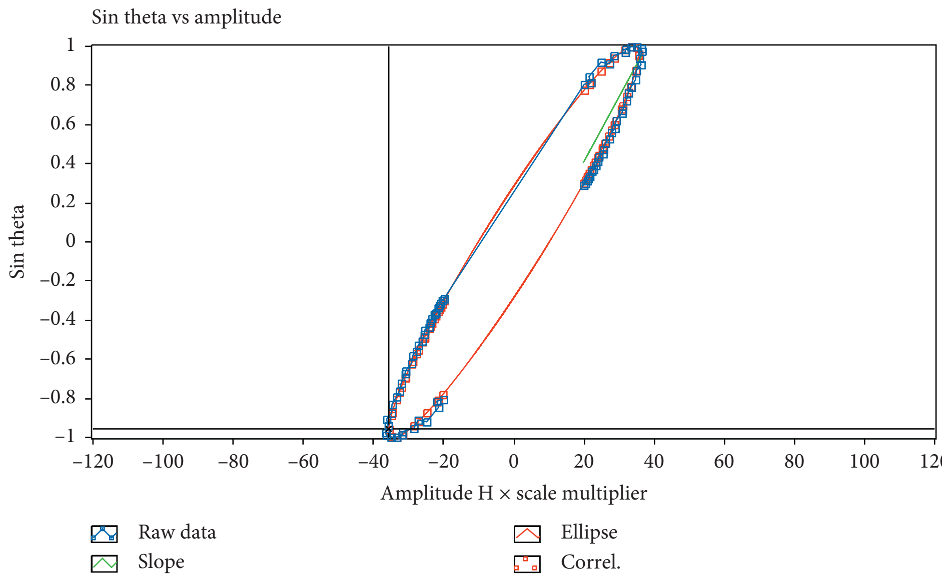
(b)

Figure 7: Ellipse area for plate A1: (a) healthy; (b) damaged.



(a)

Figure 8: Continued.



(b)

Figure 8: Ellipse area for plate B1: (a) healthy; (b) damaged.

suggests the area of the ellipse changes with damage, and there might be a possible correlation.

Again, the ellipse area for the healthy plate B1 is larger than that for the damaged plate as shown in Figure 8. Although the area of the ellipse for the damaged plate appears to be larger pictorially, in reality, it is opposite. The larger appearance was due to being multiplied by a scale multiplier of 10,000 and that of the healthy ellipse being multiplied by just 1 scale multiplier.

Obviously, from Figures 4–6, there is a variation in the area of the ellipse after the damage was introduced in the test plates. In plate A1, the area of ellipse decreased at all the 10 modes considered.

It is important to note that the amount of reduction in the ellipse areas as shown from Figures 4–6 is within the same range. Apart from specimen C3, the reduction rate across all the modes in other specimens is over 97%. The results indicate that the elliptical method is sensitive to the presence of damage in the composite CFRP rectangular plate.

4. Conclusion

A novel method for damage identification from FRF, based on the representation of the receptance on the elliptical plane, was presented. It was shown that the area of the ellipse, which is related to the modal constants (local modal properties), is sensitive to damage in a consistent manner. Hence, this paper offers new possibilities for other researchers who are concerned with damage diagnosis in lightly damped structures since the elliptical plane modal identification method provides promising results for damage identification in CFRP rectangular plates. However, more studies are still required in terms of experimental work to find what the mathematical correlation is (if any) between damage and the shape of the ellipse, for example, by taking into account that damage in CFRPs has complex morphologies that may affect the plates and how the modal constants are affected by the presence of damage.

Data Availability

The Frequency Response Functions (FRFs) data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Daerefa-a Mitsheal Amafabia and Diogo Montalvão conceived and designed the experiments. Daerefa-a Mitsheal Amafabia, Diogo Montalvão, and Opukuro David-West conducted the experiments. Daerefa-a Mitsheal Amafabia conducted the formal analysis. Opukuro David-West, Diogo Montalvão, and George Haritos supervised the work.

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References

[1] S. S. Kessler, S. M. Spearing, M. J. Atalla, C. E. S. Cesnik, and C. Soutis, "Damage detection in composite materials using frequency response methods," *Composites Part B: Engineering*, vol. 33, no. 1, pp. 87–95, 2002.

[2] L. Ye, Y. Lu, Z. Su, and G. Meng, "Functionalized composite structures for new generation airframes: a review," *Composites Science and Technology*, vol. 65, no. 9, pp. 1436–1446, 2005.

[3] D. Montalvão, A. M. R. Ribeiro, and J. A. B. Duarte-Silva, "Experimental assessment of a modal-based multi-parameter method for locating damage in composite laminates," *Experimental Mechanics*, vol. 51, no. 9, pp. 1473–1488, 2011.

[4] D. Montalvão, D. Karanatsis, A. M. R. Ribeiro, J. Arina, and R. Baxter, "An experimental study on the evolution of modal damping with damage in carbon fiber laminates," *Journal of Composite Materials*, vol. 49, no. 19, pp. 2403–2413, 2015.

[5] L. Huang, A. H. Sheikh, C.-T. Ng, and M. C. Griffith, "An efficient finite element model for buckling analysis of grid stiffened laminated composite plates," *Composite Structures*, vol. 122, pp. 41–50, 2015.

[6] D. M. Amafabia, O. David-West, D. Montalvão, and G. Haritos, "Damage detection in CFRP composite plate based on evolving modal parameters," in *Proceedings of the BSSM 12th International Conference on Advances in Experimental Mechanics*, University of Sheffield, Sheffield, UK, August 2017.

[7] S. Abrate, "Impact on laminated composites: recent advances," *Applied Mechanics Reviews*, vol. 47, no. 11, p. 517, 1994.

[8] N. M. M. Maia, R. A. B. Almeida, A. P. V. Urgueira, and R. P. C. Sampaio, "Damage detection and quantification using transmissibility," *Mechanical Systems and Signal Processing*, vol. 25, no. 7, pp. 2475–2483, 2011.

[9] D. M. Amafabia, D. Montalvão, O. David-West, and G. Haritos, "A review of structural health monitoring techniques as applied to composite structures," *SDHM Structural Durability and Health Monitoring*, vol. 11, pp. 91–147, 2017.

[10] S. W. Doebling, C. R. Farrar, M. B. Prime, and D. W. Shevitz, "Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review," No. LA--13070-MS, pp. 1–136, Los Alamos National Laboratory, Los Alamos, NM, USA, 1996.

[11] S. W. Doebling, C. R. Farrar, and M. B. Prime, "A summary review of vibration-based damage identification methods," *The Shock and Vibration Digest*, vol. 30, no. 2, pp. 91–105, 1998.

[12] D. Montalvão, N. M. M. Maia, and A. M. R. Ribeiro, "A review of vibration-based structural health monitoring with special emphasis on composite materials," *The Shock and Vibration Digest*, vol. 38, no. 4, pp. 295–324, 2006.

[13] J.-J. Sinou, "A review of damage detection and health monitoring of mechanical systems from changes in the measurement of linear and non-linear vibrations," in *Mechanical Vibrations: Measurement, Effects and Control*, pp. 643–702, Nova Science, NewYork, NY, USA, 2009.

[14] N. M. M. Maia and J. M. M. Silva, *Theoretical and Experimental Modal Analysis*, Taunton: Research Studies Press and John Wiley and Sons, Somerset, England, 1997.

[15] D. Montalvão, *A modal-based contribution to damage location in laminated composites plates*, Ph.D. thesis, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal, 2010.

[16] P. Guillaume, P. Verboven, and S. P. E. Vanlanduit, "Multisine excitations-new developments and applications in modal analysis," in *Proceedings of the 19th International Modal Analysis Conference (IMAC-XIX)*, vol. 2, pp. 1543–1549, Kissimmee, FL, USA, February 2001.

[17] N. F. Rilo, L. M. S. Ferreira, and R. A. C. P. Leal, "Low-velocity impact analysis of glass/epoxy plates," in *Proceedings of the 5th International Conference on Mechanics and Materials in Design (M2D'2006)*, vol. 110, p. 0092, Porto, Portugal, 2006.

[18] D. Montalvão and D.-a. M. Amafabia, "An alternative representation of the receptance: the "elliptical plane" and its modal properties," *Mechanical Systems and Signal Processing*, vol. 103, pp. 236–249, 2018.

[19] D. Montalvão, D. M. Amafabia, and J. M. Silva, "And yet another method for the identification of modal constants in experimental modal analysis," in *Proceedings of the 7th International Operational Modal Analysis Conference (IOMAC'17)*, Ingolstadt, Germany, May 2017.

[20] D. Montalvão, M. Dupac, D. M. Amafabia, O. David-West, and G. Haritos, "On reducing uncertainty on the elliptical plane modal identification method," *MATEC Web of Conferences*, vol. 211, Article ID 06001, 2018.