



Original Article

The modal characteristics of the CFRP, GFRP and hybrid composites exposed to HCl environment and impact loadings

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ABSTRACT

Composite materials can be subjected to low-velocity impact (LVI) loadings at various velocities in their application areas, as well as corrosive environments, causing degradation in the mechanical and dynamic properties. When the literature is reviewed, LVI loadings, aging time, fiber material, and hybridization effects on vibration characteristics have all been examined separately, but no research has looked at these aspects together. Therefore, in the current study, Carbon Fiber-Reinforced Polymer (CFRP), Glass Fiber-Reinforced Polymer (GFRP) and Carbon/Glass Fiber-Reinforced Polymer (Hybrid) composites were manufactured utilizing the Vacuum-Assisted Hand-Layup Method (VAHLM) and then exposed to corrosive environments and Low-Velocity Impact (LVI) loadings, respectively. In this context, the fabricated composites were immersed in a 10% diluted HCl solution for 1 week and 1 month and then exposed to LVI loadings at 2 and 3 m/s impact velocities. After that, vibration tests were conducted, and thus the impacts of corrosive environments and LVI loadings, as well as fiber materials and hybridization, on the modal characteristics were examined experimentally as a novelty for the current study. The study's findings showed that the natural frequencies of CFRP and GFRP composites are 159.5 and 91.5, respectively, and that CFRP composites have approximately 75% higher natural frequencies than GFRP ones due to the high stiffness of carbon fibers. On the other hand, it was determined that hybrid composites had higher damping ratios than the others, which was ascribed to elevated energy absorption caused by the various interface characteristics of carbon/glass fibers. It was also discovered that no significant changes appeared in the dynamic responses following the corrosive environment exposure and LVI loadings, which was attributed to the composites' substantial impact and corrosion resistance.

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INTRODUCTION

A corrosive environment leads to various damage mechanisms in composites such as debonding, crack prop-

agation, delamination, swelling etc. Moreover, pre-existing damage in the composite is triggered by the effects of the corrosive environment and this accelerates the degradation of the dynamic properties. For these reasons, much research

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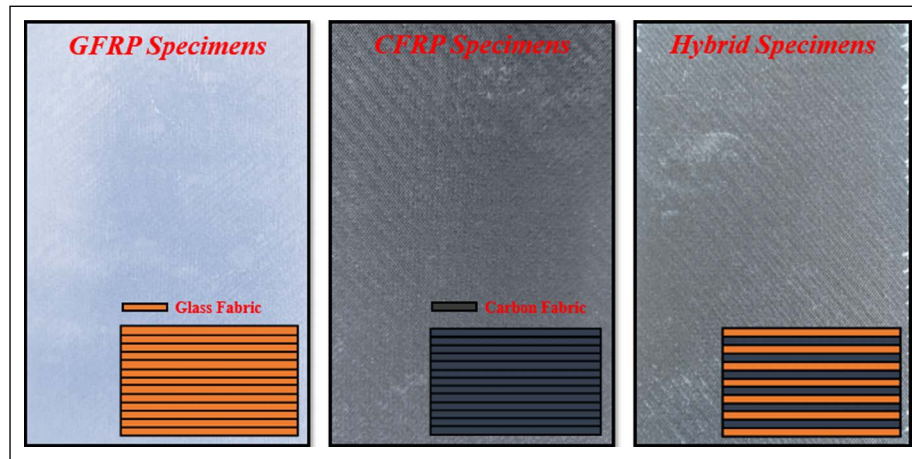
has been conducted on the corrosion resistance of composites and it is aimed at determining the effects of a corrosive environment on vibration behaviour [1–12]. For example, Ramalingam et al. [2] examined the effects of aging on biocomposites' vibration characteristics. In this regard, the impacts of various aging conditions, particularly humidity, on the dynamic behaviour of composites were studied. According to the study, as aging time climbed, so did the damping factor, whereas natural frequency responses dropped. In another study [4], the effects of hydrothermal aging on composite vibration properties were investigated experimentally. Sea water and distilled water were chosen as aging environments, and thus the effects of these media on vibration responses were examined. Furthermore, the dynamic characteristics for the aramid, glass, and aramid/glass fiber-reinforced composites were explored, as well as the impacts of fiber material, hybridization, and aging on vibration responses. The study found that aging had no significant effect on first-mode natural frequency responses, but it did raise the damping responses of hybrid ones. Moreover, aging was shown to reduce storage and loss modulus responses. In the study conducted by Senthilrajan and Venkateshwaran [5], the effects of aging on vibration responses were investigated by considering various fiber lengths and weight percentages. The study concluded that fiber density and fiber/matrix bonding strength were extremely efficient on moisture resistance, and that rising fiber density and bonding strength reduced dynamic behaviour deterioration. It was also said that water molecules attacked the fiber-matrix interface, causing debonding, which resulted in a reduction in natural frequency responses due to aging. Cheour et al. [8] subjected flax fiber-reinforced composite specimens to room-temperature water aging, and then studied their damping and mechanical properties. According to the study, it was determined that water uptake caused a reduction in flexural modulus and an increment in loss factors. To test the reversibility of these changes, the same parameters were examined after the specimens had been dried, and it was discovered that the drying process was reversible in terms of loss factors but irreversible in terms of flexural modulus. It was also indicated that fiber orientation is vital to water uptake. Xu et al. [10] studied the effects of hygrothermal aging on the mechanical properties of composites and discovered that the saturated moisture contents of pure resin and composite at 70°C were about 0.32% and 0.19%, respectively. It was revealed that following moisture absorption, the tensile strengths of the pure resin and composite retained at 81.85% and 95.49%, respectively. In another study, Oğuz et al. [11] looked at how distilled water affected the flexural and impact properties of composites. In the study, the specimens were aged at 25 and 70 °C for 1000 hours, and it was stated that the reduction in impact and flexural strength rose with ascending temperature. In a similar study, Oğuz et al. [12] examined the effect of aging in seawater on the flexural and LVI responses of composite materials. The study concluded that damage such as fiber-matrix cracking and delamination in composites also increased as the temperature elevated.

Apart from that, composite materials are frequently subjected to LVI loadings in their application areas, and this causes some damage such as delamination, fiber breakage, and matrix cracks. Moreover, these structures can be subjected to vibration at various frequencies, distortions occur in their vibration responses due to LVI-induced damages and this poses a great danger for their usage areas. For all these reasons, various research have been done to determine the vibration characteristics of composites, or the effects of LVI loading on vibration responses [13–19]. In their study, Coskun et al. [13] applied LVI loading on polyamide fiber-reinforced composites before performing an experimental investigation into the variations in vibration characteristics. The study found that using polyamide fibers resulted in a specific damping capacity of approximately 11.5%, and it was concluded that thermoplastic fibers greatly improve damping responses when compared to synthetic ones. It is also deduced that the change in vibration responses is restricted since the LVI loading acts on a limited area. In another study [15], Coskun et al. [13] integrated various thermoplastic veils into carbon and fiber-reinforced composites as interlayers, and investigated their vibration responses after LVI loading. As a consequence of the study, it was determined that loss factor responses decreased due to LVI loading and this was greater for CFRP composites compared to GFRP composites. In another study, Duan et al. [18] performed experimental LVI tests at various energy levels, examining the dynamic responses of composite materials. C-Scan tests were also used to analyse the delaminated areas following LVI loadings. Furthermore, frequency-sweep vibration tests were performed, and the damage characteristics of composites exposed to LVI stress were determined. The study found that matrix damage and delamination were the most common damage processes in composites. The results also showed that the delamination area and first-order frequency had a linear correlation, that the stiffness reduced as the delaminated area rose, and that this phenomenon resulted in a reduction in frequency responses.

Studies on the impact of aging on vibration characteristics have found that extending aging time reduces the natural frequency responses of composite materials, which is associated with stiffness loss. On the other hand, LVI loading has resulted in a reduction in natural frequencies, which has been linked to stiffness loss with damage. Furthermore, it was determined that aging and LVI loading led to more damage and friction surfaces, resulting in greater damping responses. When studies in the literature are reviewed, it is noticeable that studies that examine the vibration responses of composites exposed to corrosive environments or LVI loadings are commonly found. However, it is seen that the effects of LVI and aging on vibration responses are not examined together, and this stands out as a deficiency in the literature. Moreover, the fact that the effects of LVI and corrosive environment are not examined in terms of fiber material or hybridization constitutes another motivation for the current study. For that reason, as part of the present study, CFRP, hybrid and GFRP composites were exposed to

Table 1. Some details for the CFRP, GFRP and hybrid composites

Specimens	Length (mm)	Width (mm)	Thickness (mm)	Weight (g)	Density (kg/m ³)
CFRP	150.1	100.2	3.2	68.09	1414.77
Hybrid	149.9	100.1	3.08	72.88	1576.97
GFRP	150.1	100.1	3.03	80.03	1757.91

**Figure 1.** Visualization of the fabricated CFRP, GFRP and hybrid composites and their stacking sequence.

aging in a HCl environment for 1 week and 1 month, and then impacts were applied to the aged specimens at 2 various velocities, 2 and 3 m/s. Then, modal tests of synthetic fiber-reinforced composites exposed to corrosive environments and LVI loadings were performed under fixed-free boundary conditions, and thus changes in vibration responses were examined and gained to the literature.

MATERIAL AND METHODS

In the current study, CFRP, GFRP, and hybrid composites were fabricated and then subjected to accelerated aging, LVI loading, and vibration tests to examine the impacts of fiber material, hybridization, LVI loading, and corrosive environment on modal characteristics. In synthetic fiber-reinforced composites, 3k twill (0°/90°) carbon and twill (0°/90°) E-Glass fabrics with areal densities of 245 g/m² and 300 g/m², respectively, were employed as reinforcement materials, and thus the impacts of fiber material on dynamic responses have been studied. On the other hand, a combination of 75% LR160 resin and 25% LH160 hardener by weight was prepared as matrix material, and then the resin system was impregnated into the fabrics using the VAHLM method. The resin-impregnated fabrics were kept under vacuum at 80°C for 1 hour, and thus, by removing the air bubbles from the system, specimens with the minimum void content were fabricated. After that, the cured composite panels were machined into 100x150 mm dimensions following the ASTM D-7136 LVI test standard. CFRP and GFRP composites employed 13 layers of carbon and glass fiber, respectively, whereas hybrid composites were produced using 6 carbon and 7 glass fibers. Table 1 shows

some details such as final thickness, length, density etc. On the other hand, CFRP, GFRP and hybrid composite specimens and their stacking sequences are shown in Figure 1.

Following specimen fabrication, accelerated aging was employed to evaluate the influence of corrosive environments on CFRP, hybrid and GFR composites. In this regard, composites were placed in a 10% diluted HCl solution and subjected to a corrosive environment for one week and one month. Thus, it was possible to examine the impact of aging time and fiber material on vibration responses. Apart from that, composite specimens were impacted at two distinct velocities, 2 m/s and 3 m/s, to ascertain how LVI loadings affected vibration characteristics following corrosive exposure. In LVI tests, a 5.6 kg hemispherical tip impactor was dropped from the 20.4 and 45.9 cm heights for the impacts with 2 and 3 m/s velocities, respectively, and thus 11.2 and 25.2 J impact energy was transferred to the composite specimens. The experimental studies were carried out in accordance with the ASTM D-7136 standard, utilizing the support fixture depicted in Figure 2, with the boundary conditions set to pinned-support at four points. In LVI tests, force variations are detected as electrical signals thanks to the loadcell, and then the relevant signals are converted into force-time data using a data acquisition system and software. On the other hand, the experimental setup included anti-rebound equipment to avoid multiple impacts, and thus it can be examined how the vibration responses altered when only one impact was applied to the specimens. Figure 2 depicts the process followed to assess the effects of material effects, LVI loadings, and corrosive environments on the dynamic characteristics of composites.

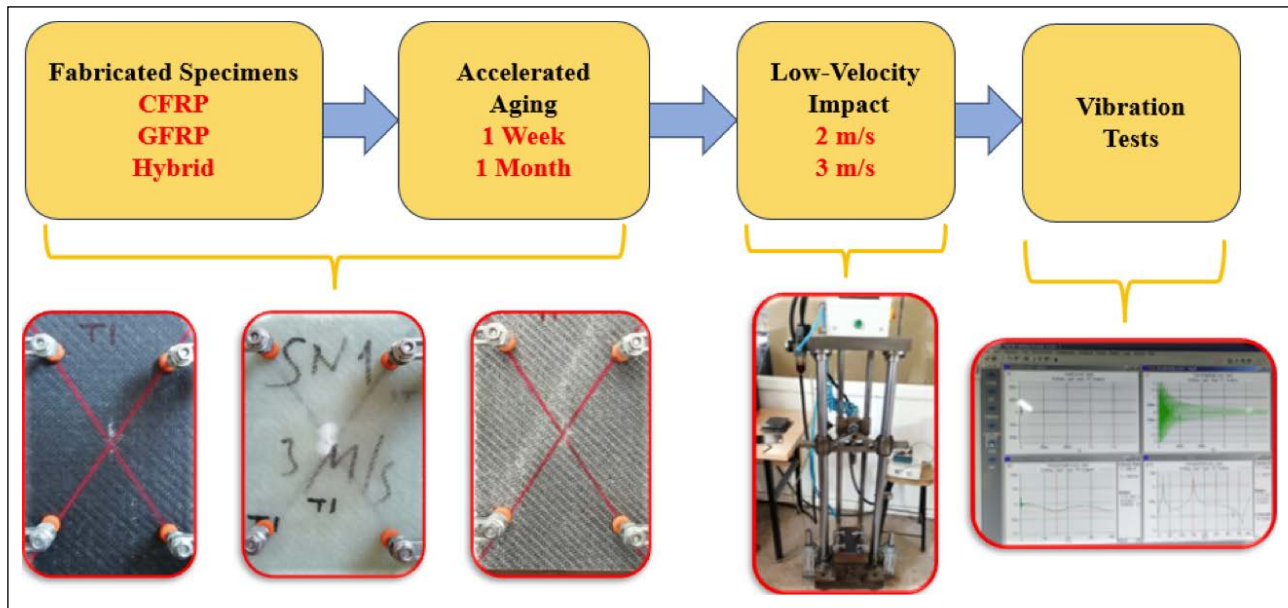


Figure 2. Flowchart for the current study.

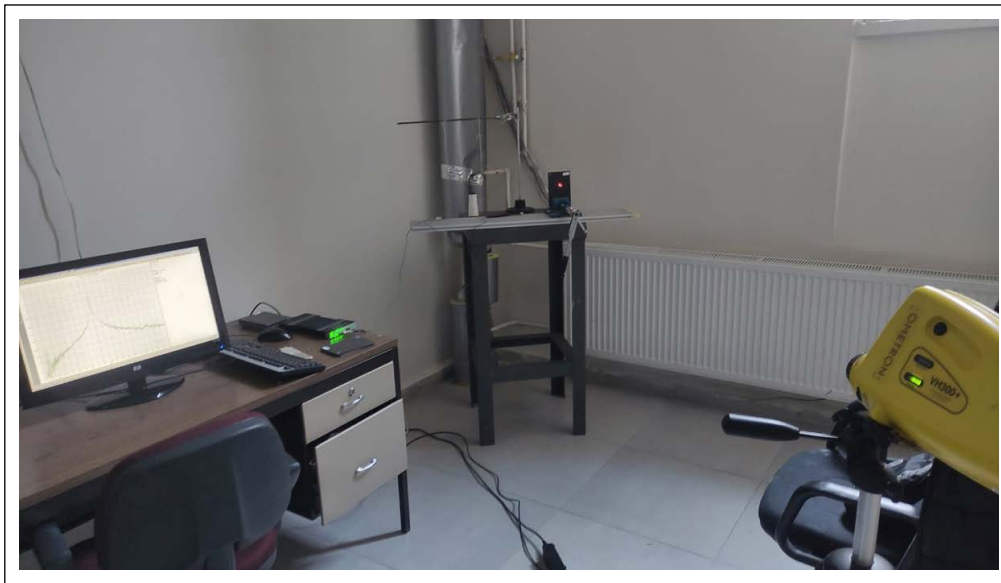


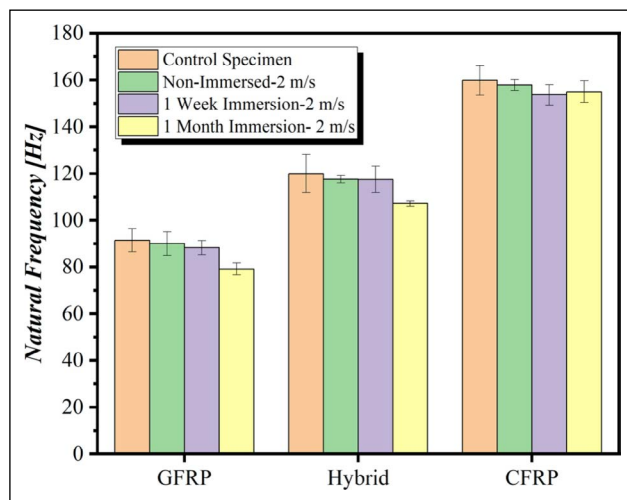
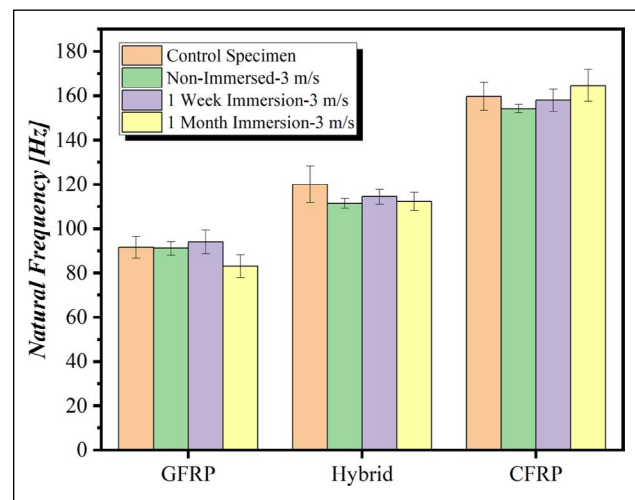
Figure 3. Experimental setup for the vibration tests.

Vibration tests were performed to examine variations in dynamic properties following exposure to corrosive environments and LVI loadings, and thus damping ratio and natural frequencies for CFRP, hybrid and GFRP composites were acquired experimentally. As shown in Figure 3, experimental studies were conducted under fixed-free boundary conditions, and amplitude-frequency data were collected from composites pushed to vibrate with an impact hammer utilizing a laser doppler in a non-contact manner. Tests were conducted using a laser Doppler vibrometer, with a 25 kHz sampling frequency and approximately 65600 data points collected for each test. A 0.5 kg impact hammer with a force sensor sensitivity of 2.25 mV/N was used in the experimental studies, and composite samples were excited with a medium-hard polymer tip. While the window method was used to eliminate spectrum leakage before

the FFT analyses, and frequency response functions (FRF) were used to fit curves and thus provide natural frequency and damping ratio responses. In this way, natural frequency responses were calculated for CFRP, hybrid and GFRP composites, and the impacts of aging time, LVI loadings, and fiber material on natural frequency were experimentally studied. On the other hand, amplitude-time data were collected for composites, and damping ratio responses were calculated using the free decay method [20] based on the hybridization, fiber material, aging time, and LVI velocity. To avoid degrading effects, vibration tests were carried out at room temperature and atmospheric pressure, and at least 3 repetitions were performed for each specimen type. Moreover, average responses and standard deviations for dynamic responses were obtained; thus, the results were found to be repeatable and reliable.

Table 2. Natural frequency and damping ratio responses for the control and non-immersed composites

	Natural Frequency (Hz)	Standard Deviation	Damping Ratio (%)	Standard Deviation
Control				
GFRP	91.5	4.929503018	0.366666667	0.029337121
Hybrid	120.0	8.221921916	0.63	0.057896459
CFRP	159.8	6.298809411	0.267833333	0.049696747
Non-Immersed (3 m/s)				
GFRP	91.1	3.090082703	0.456222222	0.099261999
Hybrid	111.3	2.179449472	0.435333333	0.094615009
CFRP	154.2	1.952562419	0.238333333	0.062044339
Non-Immersed (2 m/s)				
GFRP	90	5.006246099	0.437111111	0.132642795
Hybrid	117.5	1.5612495	0.889111111	0.092303846
CFRP	157.8333333	2.277608395	0.284888889	0.070223651

**Figure 4.** Natural frequency responses for the CFRP, hybrid and GFRP composites subjected to a corrosive environment (2 m/s impact velocity).**Figure 5.** Natural frequency responses for the CFRP, hybrid and GFRP composites subjected to a corrosive environment (3 m/s impact velocity).

RESULTS AND DISCUSSIONS

In the present study, experimental studies were conducted to assess the effects of fiber material, impact velocity, and exposure time to corrosive environments on dynamic responses. In this context, vibration responses for CFRP, hybrid and GFRP composites were obtained and comparatively examined concerning aging time and impact velocity. Figures 4 and 5 show the natural frequency responses of CFRP, hybrid and GFRP composites subjected to 2 and 3 m/s LVI loadings, respectively, varying with exposure time to the HCl environment. Moreover, numerical results for the damping ratio and natural frequencies are shown in Table 2–4. When the findings are evaluated, it is clear that GFRP and CFRP composites exhibit the lowest and highest natural frequency responses, respectively. For example, when the impact of the fiber material is taken into account for the control specimens, the natural frequencies for GFRP

and CFRP ones are observed as 91.5 and 159.8 Hz, respectively, and thus, an approximately 75% increment in natural frequencies took place compared to glass fiber-reinforced ones thanks to the carbon fiber utilization. The rise in natural frequency responses is frequently associated with high stiffness, and the responses found in the present study are attributed to the fact that carbon fabrics are stiffer than glass ones. On the other hand, the natural frequency for the hybrid control specimens was determined to be 120 Hz, and it was established that the hybrid composites had a 31% higher natural frequency than the GFRP ones. The related results were interpreted as the hybrid composites exhibited the characteristics of both fabrics and had stiffness between the GFRP and CFRP composites as expected.

When the natural frequencies for the control and non-immersed specimens were examined, a slight drop was observed, but no significant changes took place since the damaged area was localized and limited. This situation was

Table 3. Natural frequency and damping ratio responses for the 1-week immersed composites

	Natural Frequency (Hz)	Standard Deviation	Damping Ratio (%)	Standard Deviation
1 Week Immersion (3 m/s)				
GFRP	94.1	5.352828951	0.444333333	0.085777328
Hybrid	114.4	3.342695187	0.608222222	0.055703830
CFRP	157.9	4.94834428	0.311555556	0.031321363
1 Week Immersion (2 m/s)				
GFRP	88.33333333	3.041381265	0.503333333	0.10459565
Hybrid	117.4444444	5.62052291	0.403333333	0.094597833
CFRP	153.6111111	4.342938074	0.252444444	0.057591473

Table 4. Natural frequency and damping ratio responses for the 1-month immersed composites

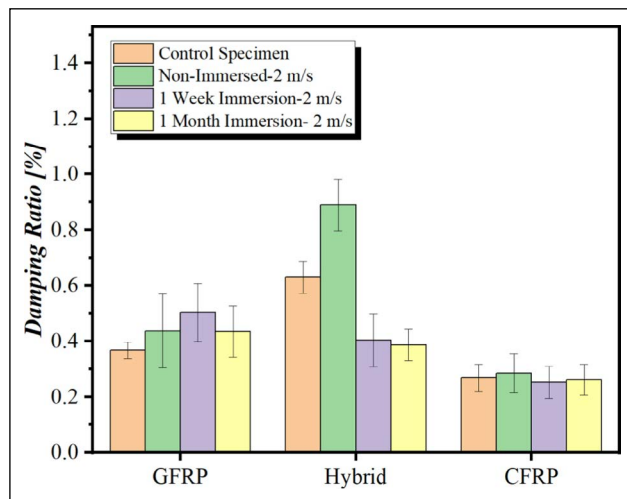
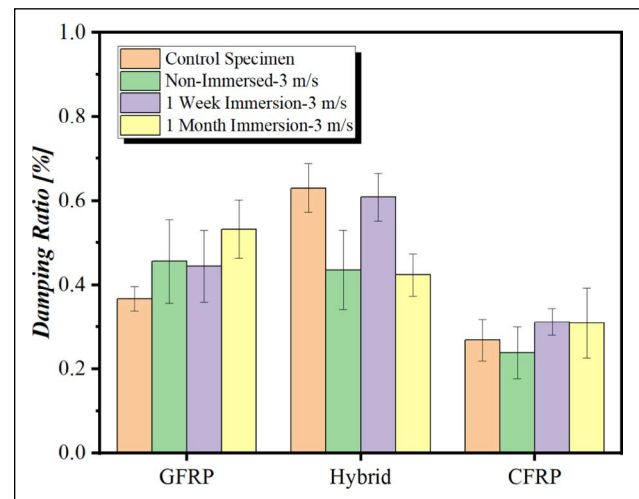
	Natural Frequency (Hz)	Standard Deviation	Damping Ratio (%)	Standard Deviation
1 Month Immersion (3 m/s)				
GFRP	83.1	5.122119787	0.532222222	0.069524776
Hybrid	112.2	4.21389896	0.423111111	0.050851363
CFRP	164.6	7.270564704	0.309111111	0.083914308
1 Month Immersion (2 m/s)				
GFRP	79.16666667	2.537222891	0.434888889	0.091769336
Hybrid	107.1111111	1.21906157	0.387	0.05652212
CFRP	155	4.562071898	0.261222222	0.055352908

interpreted as the LVI loading did not affect the composite structure too much, while the reductions in the natural frequencies were interpreted as a slight degradation in the material stiffness. On the other hand, when the impacts of the corrosive environment on modal properties were examined, it was concluded that aging had no substantial impact on natural frequencies. This situation demonstrates that the carbon/glass fiber-reinforced composites' corrosion resistance was quite high, since neither the structural integrity nor the stiffness of the relevant structures deteriorated significantly. Apart from that, when the natural frequency responses for various impact velocities are compared in Figures 4 and 5, it becomes apparent that raising the impact velocity from 2 m/s to 3 m/s has no significant effect on the findings. This demonstrates that the relevant impact velocities are insufficient to cause substantial deterioration in structural integrity, as well as no significant degradation in the dynamic properties of composites subjected to local damage. When the relevant studies in the literature are examined, it is stated that the change in the modal responses is not significant in the case of a limited impact area. For example, Srihi et al. [21] investigated vibration responses following LVI and discovered that, while there was a reduction in natural frequencies as energy increased, the reduction was fairly minimal in some modes. In another work, Katunin et al. [22] investigated the damage analysis and modal responses of various composite structures and discovered that modal parameters were not significantly sensitive to minor damage in local areas.

In their application areas, composite materials can be subjected to vibration loadings at various frequencies, and structures can exhibit vibration with extremely large amplitudes in the case of resonance. This situation induces critical stresses, causing components to lose functionality and get damaged. On the other hand, inherent damping is a crucial material property and can be defined as the amount of energy absorbed within the material [23]. In the case of resonance, vibration movement is reduced in materials with relatively higher inherent damping in a shorter time, reducing the probability of damage. On the other hand, composite materials may be subjected to a variety of corrosive environments in their application areas, which can cause a degradation in vibration properties, particularly in the damping ratio. For that reason, in the present study, vibration tests have been conducted to assess the effects of impact velocity and aging time on the damping ratios, and related responses were presented comparatively for CFRP, GFRP and hybrid composites in Figures 6 and 7. When damping properties are evaluated, it becomes apparent that the LVI loadings induce a slight increase in damping ratios, but no substantial changes take place. This situation demonstrates that the impact and aging cause little structural integrity deterioration; however, raises in damping ratios are attributed to composite damages, resulting in a slight rise in energy absorption. When the studies on the relevant modal characteristics are eval-

Table 5. T-test responses obtained for the vibration properties

Material	Response	Group 1	Group 2	T-statistic	P-Value	Significance
GFRP	Natural Freq.	Control	1 Week Immersion (3 m/s)	-2.23	0.0412	Yes
GFRP	Damping Ratio	Control	1 Month Immersion (3 m/s)	2.45	0.0278	Yes
Hybrid	Damping Ratio	Control	Non-Immersed (3 m/s)	-2.31	0.0325	Yes
CFRP	Natural Freq.	Control	1 Month Immersion (2 m/s)	2.58	0.0189	Yes
CFRP	Damping Ratio	Control	1 Week Immersion (2 m/s)	-3.12	0.0093	Yes
Other Combinations	–	–	–	–	$p \geq 0.05$	No

**Figure 6.** Damping ratio responses for the CFRP, hybrid and GFRP composites subjected to a corrosive environment (2 m/s impact velocity).**Figure 7.** Damping ratio responses for the CFRP, hybrid and GFRP composites subjected to a corrosive environment (3 m/s impact velocity).

uated, it is obvious that the amount of change in the responses varies based on the moisture absorption, and that there were no substantial changes in the responses when the absorption was inadequate. For example, Namrata et al. [24] discovered that moisture absorption in the composite raised due to the aging effect, which somewhat elevated the samples' mass while partially reducing their natural frequencies. However, they reported that high water absorption resulted in a considerably more profound reduction. In another study conducted by Mayya et al. [25], it was stated that moisture absorption is one of the most important parameters affecting the mechanical properties of marine structures, and that pH change and moisture absorption weaken the stiffness and bending properties.

On the other hand, when the impacts of fiber material on composite damping were evaluated, hybrid composites were shown to have higher damping ratios than GFRP and CFRP ones. This was attributable to the various interface characteristics of glass and carbon fibers, resulting in an increment in internal energy distribution. Apart from that, unusual fluctuations in damping responses were detected,

which were attributable to structural differences in the composites, experimental disturbances, and production-related variations. A t-test was used to assess the significance of the vibration data, and thus p values were obtained from relevant tests, taking into account composite materials, accelerated aging, and LVI effects. When the data were evaluated, as indicated in Table 5, it was discovered that the responses were significant and the findings were reliable.

CONCLUSION

In the current study, CFRP, GFRP and hybrid composites were produced and subjected to vibration tests to determine the impacts of fiber material, LVI loading and corrosive environments on the vibration characteristics of composites. In addition to the control specimens, the dynamic responses for composites subjected to various impact velocities and immersed in 10% diluted HCl environments were experimentally achieved and presented comparatively. The following are some significant outcomes from the present study:

- Natural frequency responses for GFRP, hybrid, and CFRP control specimens were found to be 91.5, 120, and 159.8 Hz, respectively, and the utilization of carbon fibers resulted in a 75% increment in natural frequencies when compared to GFRP. The relevant findings demonstrate that CFRP composites exhibit the highest natural frequency, which is ascribed to the relatively greater stiffness of carbon fibers. On the other hand, hybrid ones were observed to exhibit the common characteristics of both composites and, as expected, exhibited a natural frequency between CFRP and GFRP composites.
- It was determined that there was no significant change in the dynamic characteristics of the composites exposed to the HCl environment. This was ascribed to the excellent corrosion resistance of synthetic fiber-reinforced composites and thus no significant changes in the structural integrity.
- Examining how LVI loading affects the natural frequencies reveals that there is a slight reduction due to the impact, but no notable alterations take place because the damaged area is limited and local. Similarly, it was determined that there were no significant changes in the vibration responses as a consequence of ascending the impact velocity from 2 m/s to 3 m/s, and this was interpreted as the impacts at the relevant velocities did not cause significant degradation in the material stiffness.
- When the damping ratios for CFRP, GFRP, and hybrid composites were examined, the hybrids demonstrated the highest damping ratios. The relevant responses were attributed to the differences in interface characteristics between glass and carbon fabrics, which were interpreted as enhanced energy absorption within the structure.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Betül Sözen Coşkun: Methodology, investigation, visualization, writing – original draft, editing.

Taner Coşkun: Methodology, investigation, visualization, writing – original draft, editing.

Serkan Kapici: Experimental tests, specimen fabrication.

Yavuz Selim Tarih: Experimental tests.

Ömer Sinan Şahin: Conceptualization, validation, editing.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Statement on the Use of Artificial Intelligence

Artificial intelligence was not used in the preparation of the article.

Ethics

There are no ethical issues with the publication of this manuscript.

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